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PITT RIVERS MUSEUM
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Notes on Prehistoric and Early Iron in the Old World

BY

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INCLUDING

*A Metallographic and Metallurgical Examination
of specimens selected by the Pitt Rivers Museum*

*by courtesy of the Director of Research and Technical Development
of Messrs. Stewarts and Lloyds*

AND CONTRIBUTIONS BY

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Occasional Papers on Technology, 8

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PREFACE

THE author of the present *Notes on Prehistoric and Early Iron in the Old World* has already published *Notes on the Prehistoric Metallurgy of Copper and Bronze in the Old World* in this series, and the steady demand for this book and requests for a similar work on iron have led us to offer such a work as the eighth of our *Occasional Papers on Technology*. Mr. Coghlan is well qualified to follow our general method in this series. In his early days as a pupil in a large engineering works he learned the actual methods and practice in the forge and foundry. Before devoting his attention to archaeology and ethnology and later to the direction of a museum, he had over twenty years of experience as a chartered mechanical engineer, and had much experience in the laboratory testing the materials of construction, including especially iron, copper, and bronze. His interest in prehistoric and primitive metallurgy began during his work in Burma, where he had ample opportunity to study primitive metallurgical processes at first hand.

For some years he has been Chairman of the Ancient Mining and Metallurgy Committee of the Royal Anthropological Institute, of which the Curator of the Pitt Rivers Museum is also a member, and for this book they have been most fortunate, through the good offices of the British Iron and Steel Research Association, to enlist the services of the great firm of Messrs. Stewarts & Lloyds, whose Director of Research and Technical Development gave permission for the metallographic and metallurgical examination of a number of important specimens, the work being carried out under the direction of Mr. T. H. Williams, Manager, Chemical Research, and of Mr. P. Whitaker, Manager, Metallurgical Research. We are deeply grateful to them for the care and interest they showed in the preparation of reports on iron objects ranging from about 800 B.C. to after A.D. 1000, thus helping us towards making a skeleton picture of what the blacksmith knew over a long period of time, and helping materially to fill gaps in the collected records of other workers. In some examples, further information could have been given if the terms of reference had allowed sectioning of the objects.

One of our considerable duties was to find iron from so many periods and areas which was capable of yielding useful results to the analysts, for iron is a most perishable material, and much of the evidence for which we

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sought would have vanished with corrosion. Thus we had to collect a great deal of material in order to choose some that was sound enough to be worth analysing. We are glad here to record our thanks to Mr. D. B. Harden, Keeper of the Department of Antiquities in the Ashmolean Museum for iron from Syria, Jugoslavia, and elsewhere in Europe, ranging from 600 B.C. to Mediaeval times, to Miss Olga Tufnell of the Wellcome-Marston Archaeological Research Expedition to the Near East for iron from ancient Lachish of the sixth century B.C., and to Mr. Richard Barnett of the Department of Egyptian and Assyrian Antiquities of the British Museum for iron from Nimrud of the eighth century B.C. To Dr. Karl Kromer of the *Prähistorische Sammlung im Naturhistorischen Museum*, Vienna, we are indebted for Hallstatt iron of about 600 B.C., and to Professor Dr. Alfred Bühler of the *Museum für Völkerkunde* of Basel for obtaining two La Tène swords of about 50 B.C. from the *Historisches Museum*, Basel, which we were allowed to analyse. Mr. W. A. Smallcombe, Director of the Reading Museum and Art Gallery, kindly lent us a Roman axe of the fourth century A.D. from Silchester, and a Saxon axe, and the author supplied the fine Danish axe of the ninth century A.D. Among others who helped us in our search for suitable iron, we are happy to thank Mr. Seton Lloyd of the British School at Ankara, Dr. Claude F. A. Schaeffer of St. Germain-en-Laye, Mr. A. H. S. Megaw of Nicosia, Mr. W. F. Grimes and the Roman and Mediaeval London Excavation Council, Dr. G. H. S. Bushnell, Curator of the University Museum of Archaeology and Ethnology, University of Cambridge, and Mr. H. St. George Gray. To name all who have helped would indeed be difficult. The file of letters about this book, if printed, would be as long as the book.

For permission to reproduce figures and use material already published, we are indebted to M. Edmond P. Fouss, Conservateur, Musée Gaumais, and M. A. France-Lanord, Mr. J. W. Lillico, Professor Dr. R. J. Forbes, Messrs. Johann Ambrosius Barth (for work by Weiershausen and Ohlhaver), Dr. Menzel of the *Römisch-Germanisches Zentral-museum*, Mainz, for permission to use figures by Lindenschmit, the *Deutsches Archäologisches Institut*, Frankfurt, for the use of figures by Witter, Professor Gordon Childe for permission to use figures published by the University of London Institute of Archaeology, and to Professor R. Pittioni.

Our thanks are due to Mr. G. C. Boon of the Reading Museum for advice and information concerning heavy Roman iron forging, to Mr.

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W. L. Brown of the Ashmolean Museum for most valuable advice and information in the preparation of Chapter IV, to Mr. H. J. Case of the Ashmolean Museum for reading the chapter and advising us, and to Dr. William Cohn of the Museum of Eastern Art for much help and advice. We are glad, too, of the opportunity to thank Professor Joseph Needham of the University of Cambridge for a long and valuable correspondence in which he placed at our disposal much of the material on ancient Chinese cast iron which he has collected for future volumes of his great work on *Science and Civilization in China*, now being published by the Syndics of the Cambridge University Press.

Finally, it is a great pleasure to thank Mr. K. H. H. Walters and Mr. I. M. Allen of the Pitt Rivers Museum for all the time and care they spent in sorting and preparing illustrations for the Press, Mr. R. C. Gurden, Secretary and Librarian of the Museum, for work on the bibliography and text, and the Staff of the University Press for the care and trouble and beautiful craftsmanship they always spend on our books.

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Chapter I

THE IRON ORES AND ANCIENT MINING

IRON ORES AND THEIR DISTRIBUTION

FROM a technical and cultural point of view it may be considered that the discovery of iron was not an event of the same importance as that of the discovery of how to extract copper from its ores, for it may be argued that copper and its various alloys could, in some measure, have taken the place of iron, although at a greatly increased cost and with much reduced efficiency. However, it cannot be disputed that the discovery of iron was also of the very greatest importance in the evolution of metallurgy. The discovery opened up an entirely new field in that it led to the availability of a vast quantity of relatively cheap metal which was of a nature much more suitable to the manufacture of tools and weapons than the non-ferrous alloys could be. Also iron is, of course, well suited to a wide range of domestic and general use. In dealing with early iron we must consider that obtained from two sources:

- (a) Iron which is obtained from the ores.
- (b) Meteoric and natural iron.

Consider, first, metal obtained from the ores. It is of course well known that iron ores do not resemble in appearance the metallic iron which can be extracted from them. In many cases the ores are earthy-looking substances bearing no superficial relationship to the desired metal. Heat and the chemical process termed reduction are required in order to extract the metal from the parent ore; this is also known as the smelting process. The ores from which iron is obtained are extremely plentiful and widely distributed; indeed, next to aluminium, iron is the most widely distributed of all the metallic elements. The quantity of iron contained in the various ores varies considerably, and in order that the ore may be worth working the percentage of iron which can be extracted by smelting must be reasonably high, for example, 20 per cent. and upwards. Iron ores are usually classified as sedimentary, crystalline, and replacement. In general, it is not necessary for the archaeologist to concern himself with the complex details of the mode of formation of the metalliferous ores. The

following remarks by Fearnside and Bulman (1944, p. 115) will indicate the differences in the general classification:

Most iron ores carry the metal in the form of oxides, carbonate or silicate, and contain at least 20 per cent of iron. The usual classification is into sedimentary, crystalline and replacement ores. A sedimentary ore is a deposit of hydrated oxide, carbonate or silicate, formed by precipitation, which is part (sometimes nearly the whole) of a bed of sediment; in a replacement ore, the iron has been brought in subsequently by solutions, which by interaction have replaced the original, generally calcareous, rock. There are also high-grade magnetite ores, formed at high temperature by crystallization of excess of iron in igneous and metamorphic rocks. These last are of great importance in Sweden, Russia and Eastern America.

Of the various iron ores, some are suitable for smelting by a primitive people, while others are unsuitable for primitive methods of smelting. This aspect of the question will be considered later on. The following ores may be mentioned:

- OXIDE ORES. Haematite, Fe_2O_3 .
 Magnetite, Fe_3O_4 (sometimes known as lode-stone).
 Limonite, $2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$.
- SULPHIDE. Iron pyrites and Marcasite, FeS_2 (iron disulphide).
 Pyrrhotite, Fe_7S_8 (the magnetic sulphide)
- CARBONATE. Spathic ore or Siderite, FeCO_3 .

Rastall (1923, p. 314) gives the following figures of the iron content for certain ores:

Magnetite.	Iron content when pure	72.4 per cent.
Haematite.	„ „	70.0 „
Goethite	„ „	62.9 „
Limonite.	„ „	Variable.
Pyrite.	„ „	46.6 per cent.
Chalybite (Siderite), Spathic iron ore	FeCO_3 ,	content of 48.3 per cent.

Haematite, magnetite, and limonite were of importance in the early processes. Of these Professor Park (1925, p. 185) says:

MAGNETITE. This mineral is commonly found in igneous and crystalline rocks. It occurs in thick beds, irregular masses frequently of great extent, and as small grains disseminated throughout many igneous and altered rocks. In rocks subject to weathering it changes first to the carbonate and then to the brown or red peroxide. Hence sands, gravels, and compact rocks containing magnetite soon assume a rusty-brown colour on the surface when exposed to the action of air and water.

HAEMATITE. This valuable ore of iron occurs as beds interstratified with sedimentary and schistose rocks, and as a constituent of many mineral veins.

THE IRON ORES AND ANCIENT MINING

LIMONITE. This ore occurs in beds and irregular deposits in stratified formations, and as the gossan or cap of sulphide lodes. In the form of bog-iron¹ it is frequently found in irregular sheets on the lake bottoms and in marsh lands where it has been deposited by the action of organic acids or iron bacteria. This is the oxide of iron which gives the prevailing yellow or rusty-brown colour to soils, clays, sands, and many sandstones.

Concerning the iron content of the following ores, Forbes (1950, p. 381) gives some figures of interest:

Limonite (Brown iron ore, Brauneisenerz) has a theoretical iron content of 59.9 per cent., and a practical iron content of 25–58 per cent.

Oolitic iron ore. Practical iron content of 24–46 per cent.

Bog-ore (Limonite, Raseneisenerz) has a practical iron content of 35–55 per cent.

Spathic iron (Siderite, Spateisenstein) has a theoretical iron content of 48.3 per cent., and a practical iron content of 30–44 per cent.

Blackband (Kohleneisenstein), practical iron content of 36–40 per cent.

The actual distribution of iron ore in the Old World is a matter which cannot here be gone into in any detail. As we have previously mentioned, iron ores are so common and so widely distributed that it would be a long and difficult task to give anything like a comprehensive list of the known deposits. The famous Hallstatt iron, and other important European deposits, are well known. For the most ancient iron working certain deposits are of considerable importance and the following mentioned by Gowland (1912, pp. 281 ff.) are of interest. In western Asia there are two important districts where iron ores are of very extensive occurrence: one is the region on the south-east of the Euxine (ancient Paphlagonia and Pontus), extending from the modern Yeshil Irmak to Batum; the other is the Taurus and Anti-Taurus region on the south-east of Asia Minor, extending on the west from Cape Anamur to the borders of Syria and in Syria to Aleppo, the Euphrates, and Lebanon. Iron ore is also found in the Tiyyari Mountains to the north-east of the site of Nineveh and in the neighbouring part of Kurdistan. It is also recorded that Ashur-nasir-pal (885–860 B.C.) obtained iron in the neighbourhood of Carchemish. In

¹ Park's *A Text-Book of Geology*, London, 1925, p. 443, defines bog-iron ore as 'an impure hydrated peroxide of iron which frequently forms on the bottom of swamps and shallow lagoons'. Of the mode of deposition he says (p. 32), 'Rain water in its passage through rocks containing sulphides frequently becomes charged with iron salts. When the water issues at the surface the iron, through the action of the atmospheric carbon dioxide, is converted into the ferrous carbonate. The carbonate is rapidly oxidised by the oxygen of the air into the hydrous oxide, which falls as a yellow or foxy brown precipitate. In this way are formed the limonite (hydrous peroxide of iron) veins so frequently found traversing ferruginous sandstones and altered igneous rocks. The variety of the hydrous peroxide known as bog-iron ore is formed in the bottom of swamps and lagoons by the same series of reactions, aided by the operations of certain species of bacteria.'

northern Persia, in the neighbourhood of Parpa, between Kerman and Shiras and not far from Persepolis, there are extensive remains of early iron workings which were doubtless the source of the vast numbers of iron implements and objects found on the plain in the vicinity of that ancient city. Also in northern Persia in the Karadagh district mounds of prehistoric iron slag of enormous extent have been found. Gowland also states that in India iron ores have been worked in early times in the North-West Provinces, the Western Ghats, Mysore, Madras, and Hyderabad, also in central Asia.

For a more detailed survey, Professor R. J. Forbes (1950, pp. 380 ff.) may be consulted with advantage. He gives a most useful map showing some of the more important iron ore deposits of the Ancient Near East.

ANCIENT MINING

The study of prehistoric iron calls for some consideration of mining in general, of copper as well as of iron. Ancient mining long predates the discovery of iron, for in the Neolithic period of western Europe pit and gallery mining go back to the well-known flint mines such as Grimes Graves in Norfolk and Spiennes in Belgium, where shafts reached to as much as 50 feet in depth.¹ This was the mining of flint and other stone for the production of tools and weapons. According to Professor R. J. Forbes (1950, p. 43) the earliest traces of such mining go back to Palaeolithic times when certain centres mined flint and exported it over considerable distances. However, in the Neolithic period the trade materially increased and became important. The history of ancient mining is a subject which covers a vast field. Much work has been accomplished by Oliver Davies, C. E. N. Bromehead, and the invaluable research of Professor Pittioni and others. However, owing to the relatively small amount of field work, and evidence from mining experts, it cannot be said that the study is as yet far advanced. There is still need for further examination of ancient mines in the manner of von Miske's work on the early Hallstatt mines at Velem St. Veit in western Hungary, and of Professor Pittioni's and Dr. Franz Hampl's researches in Austria.

Although there is now evidence to prove the early smelting of the sulphide ores of copper in the European Alpine zone, iron ores are so plentiful and widespread as compared with those of copper that there would have been no need for intensive mining (Clark 1952, p. 201). Hence, it is probable that the material for the first prehistoric iron smelting was not

¹ For a modern review of flint mining see Clark (1952, pp. 174-82).

mined in the modern sense of the term, the ore being merely collected from surface workings. In an important paper on the 'Evidence for Ancient Mining' Mr. Bromehead (1940, p. 110) says that in certain Iron Age workings in Jutland the ore used was a superficial limonite pan, and that such workings must have been common all over Europe. Evidence for these superficial workings is no doubt difficult to detect, but there is little doubt that they may account for much prehistoric iron production. Of a far more advanced nature were the Velem mines, of which Bromehead remarks that the original open-cast was 40 feet in diameter. This was fully explored to a depth of 18 feet, but it was considered that there must have been a shaft to 200 feet. The ore was siderite, and a roasting operation involving charcoal fuel appears to have been used; fire-setting was employed, and the extracted ore was broken up by means of heavy stone mauls. These and other tools are illustrated in von Miske's report (1929, p. 82).

In Britain we have little evidence for actual iron mining before the Roman period. Iron was worked in this country from late Hallstatt or early La Tène times, but the ore was probably obtained by collecting or open-cast methods rather than by true mining. Bromehead (1947, p. 361) states that in and around the Forest of Dean there were many iron works, and in some cases extensive mines. At Coleford a large pit 20 to 30 yards in diameter was excavated and the ore vein followed by galleries. Again, at Great Doward is a large cavelike aperture with galleries running from it. At Lydney there is a sloping shaft which bears the marks of pointed picks on its walls; the entrance to the shaft was blocked by a Romano-British hut dating from towards the end of the third century A.D., by which time the mine must have been abandoned.

When suitable iron ore could be obtained by the extremely simple open-cast system it was naturally adopted during Roman and later times as indeed it is today. In his paper on 'Practical Geology in Ancient Britain' Mr. Bromehead gives evidence in support of this practice. Even during the Bronze Age mining had progressed to the extent of employing what is known as fire-setting to facilitate the extraction of the ore, and the miners' tools had also improved. Oliver Davies (1935, pp. 32-38) makes the following useful comments upon ancient mining tools: The Greeks and Romans normally used iron tools. As similar needs have evolved similar types, there is little difference between the pre-Roman, Roman, and Mediaeval tools. For earth or soft rock a pick was used which

was little longer than the modern geological hammer, but at Laurium specimens up to 15 inches in length have been found. For harder rock a gad was used which was driven in with a hammer. Crowbars were no doubt also used to lever out pieces of rock, and iron or bronze hammers were also very necessary. Of these, specimens have been recorded.

Wooden picks were used in the Cornish placers as late as the early Middle Ages, and wooden shovels also survived to at least the same time. At the Mitterberg Pittioni records short-handled wooden shovels which were used for loading ore into wooden troughs and tubs. Long-handled shovels no doubt existed like those from the Hallstatt salt mines. Horn is too soft for rock working and was probably replaced by iron before the Roman period. Implements of copper or bronze are also unsuitable for work on a rock face, being more expensive than iron, and either too soft or too brittle. Although iron is likely to have replaced stone as a material for chipping tools, stone remained long in use for the hammer. Rilled hammers, or grooved stone mauls, are particularly associated with mining, and they have a very wide distribution. In form, these stone mauls are very simple, consisting of an ovoid, or sometimes conical stone with a groove cut around the circumference at about the middle, the purpose of the groove being to provide an anchorage for the hide thongs by which the maul was secured to its haft. The weight of the maul varies widely: usually it is from 5 lb. to 8 lb., but mauls weighing up to 30 lb. have been recorded. Such extremely heavy hammers would no doubt have been handled by two men (Coghlan, 1945-7, p. 191). The grooved stone maul is of considerable antiquity, appearing during the third millennium B.C., in the Near East. The type is very well represented in mining districts of Spain and Ireland, and may well have survived the Roman period in Europe.

In many prehistoric mines the tools used by the miner were mainly stone mauls and deer-antler picks. Such implements would not be efficient for breaking up and extracting the ore. But fire-setting could have made the work, if not easy, at least quite practicable. In this operation a large fire was built up against the ore-face, and the heat from the fire and subsequent rapid cooling caused by throwing cold water upon the heated surfaces, caused a certain disintegration or shattering of the rock; this shattering would extend to some depth. After the fire had burnt out the ore could easily be picked away from the face of the working. Fire-setting has been recorded from several ancient European mines, and in his scientific research in the Austrian Alps (Salzburg and Tyrol regions),

Professor Pittioni (1948, p. 133) has shown that the development and extraction of the mines were carried out by fire-setting, the loosened material being detached by means of hammers of stone or bronze, and bronze gads. Oliver Davies points to evidence for probable fire-setting in the galleries in Etruria, at Aramo, as well as at the Mitterberg. The technique has the disadvantage that, unless some means of ventilation can be arranged, the smoke from the fire will render the mine workings uninhabitable.

The work of Pittioni, Zschocke, and Preuschen has thrown much light upon the mining technique of the alpine mining region. It is of interest to note Pittioni's statement that the prehistoric miner did not know of shaft-sinking or cross-cutting, but could only drive forward the open-cast at the outcrop on a slightly inclined plane. As a result of many years of work Zschocke and Preuschen have been able to reconstruct the prehistoric process of mining in the Alpine region (Pittioni, 1951, pp. 16-43). Fig. 1, pts. 1-4 (after Pittioni, 1951, pp. 22-23) will make the sequence of operations clear. First, with the aid of fire-setting and manual labour, a small inclined open-cast was made (Fig. 1 and A). As soon as the open-cast began to exceed a man's height, the cut was timbered over (Fig. 1, pt. 2), rejected parts of the lode body and rock debris being piled upon the timber roof. Hot air from the fire escaped upwards by the passage *F* while fresh air was induced through the gallery *S*. The resultant natural ventilation rendered the mine habitable. Sometimes another fire could be started as in Fig. 1, pt. 3, B. The extraction of ore had now passed the preparatory stage and it was usually advisable to start a second open-cast at some distance above the first one, Fig. 1, pt. 3, A. Eventually these two open-casts would join up (Fig. 1, pt. 4, B and C). It will be observed that, while the method of excavation is open-cast, the mine is of the inclined gallery type with ventilating passages. Pittioni mentions that when water seeped into the workings it was probably dealt with by building a dam at the bottom of the gallery and removing the water by bailing. Also, water from an upper adit could be drained off into a lower adit as soon as the exploitation of the lower adit had been completed. In recent mining these accumulations of water are dreaded because, should a modern working penetrate into a water-logged prehistoric gallery, disastrous flooding might result. At the Mitterberg the magnitude of the operations may be judged from the fact that the deepest point reached was 100 metres measured from the crest of the ridge. The thoroughness of the extraction is shown by the fact that the ore had

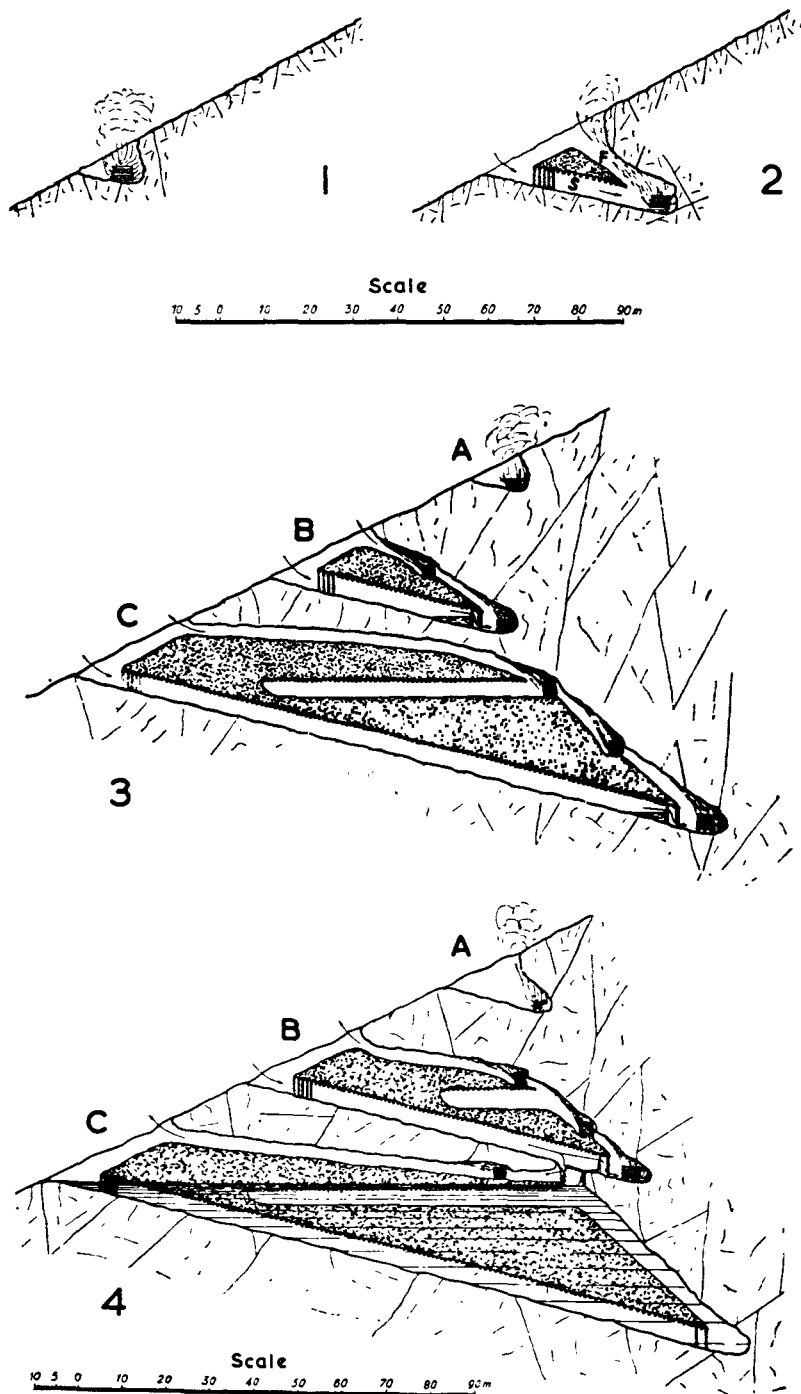


FIG. 1, parts 1-4. Stages in the development of a series of open-casts. (Pittioni 1951, pp. 22-23)

been completely removed in all parts of the lode where fire-setting had been used.

In general, it is doubtful if any true shaft mining for iron or copper was practised in prehistoric times. As Pittioni has shown, the important Mitterberg mines were worked by a combination of open-cast and adit mining. It is clear that it would have been pointless to engage in the more difficult operation of deep-shaft mining so long as ample supplies of suitable ore were obtainable merely by collecting, or through simple open-cast workings. When we come to Roman mines we find very considerable technical advance. The following points mentioned by Mr. Bromehead (1940, pp. 111-12) give some idea of this progress. In Roman mines the shafts were $2\frac{1}{2}$ to 3 feet in diameter; in these small-diameter shafts foot-holds were cut and ladders were not used. The miners usually gained access to the mine through adits, while the shafts served for ventilation and winding. Sometimes the adits were of great length, one has been recorded as 2,000 yards in length. In the relatively deep Roman mines of Spain and Portugal water had to be kept at bay. One method of accomplishing this was by hand-bailing; a chain of water-bearers was engaged continuously in this laborious process.

In some Roman mines in Portugal the adits were of very considerable size, and contained a sunken channel to carry water along one side of the adit. In these mines the water was apparently raised by means of a chain of buckets worked by animal power. In some cases where the formation of a hillside made it possible, drainage could be effected by cross-cuts at a deep level; at the Rio Tinto mines in Spain thirteen such drainage tunnels were recorded. Another method of lifting the mine water was by means of water wheels; in the San Domingos mine, not far from Rio Tinto, there was a series of mine wheels $14\frac{1}{2}$ feet in diameter working in a gallery which was inclined at 40 degrees. Again, the Romans used the Archimedean screw for lifting water. An example of an Archimedean screw pump was found in the Roman workings of the Centenillo mine in the Limares district.¹ These screw pumps were worked by slaves, and according to Rickard were clumsy and ineffective. The lift of the pump was only about 5 feet, so that 20 such pumps would have been needed to raise the mine water through a distance of 100 feet. With these primitive methods, pumping had to be carried out in stages and the total lift attained was limited.

¹ Rickard (1932, i, pp. 422-4, and fig. 49). San Domingos Mine: see Rickard, *op. cit.*, p. 427, and Nash, *The Rio Tinto Mine* (1904, p. 35).

Forbes (1950, p. 55) considers that transport of the ore was arranged in the most simple manner. Wooden or wicker trays drawn along the gallery floor served for underground haulage. In later mines operated with shafts, manual labour, using baskets or leather sacks, would be employed to carry the ore to the pit-head. There does not appear to be any strong evidence to prove the general use of the pulley for lifting baskets in Roman mines, but Oliver Davies (1935, p. 31) mentions that the Brad museum possesses from Ruda two hubs which are almost certainly pulley axles, and another, perhaps pre-Roman, is reported from Selvena. Again, Forbes (1950, p. 56) says that in some cases, such as in mines at Paros, remains of hoisting machinery have been found. It is therefore probable that the pulley and windlass were used in some mines during Roman times. By then, it is clear that the technique of mining and the development of the mines had advanced to a considerable degree. Indeed, some of the large Roman mines may be said to be engineering works of considerable magnitude.

In this country iron working became an important industry under the Romans. Soon after the conquest the Kentish Wealden deposits were worked on a large scale. Here, slag heaps which have been dated to the Roman period are numerous and of very considerable size; the Forest of Dean was also a very important centre of the iron industry. The Weald of Kent and the Forest of Dean were, in fact, the great centres of Roman iron production, but iron was worked in many other parts of Roman Britain. Collingwood and Myres (1936, p. 232) mention Warwickshire, Northamptonshire, Rutland, Norfolk, Lancashire, Nottinghamshire, Cheshire, and Northumberland as other areas of production. Although nothing is actually known of the management and ownership of the iron mines of Britain, it is of interest to quote some observations made by Collingwood and Myres (*op. cit.*, pp. 233-4).

In the Empire at large iron was normally produced by independent labourers in the forests and this may have been so in many parts of Britain; but here and there such facts as the great size of the Wealden slag-heaps, the advanced mining methods of the Forest of Dean, or the concentration of smelting works at a town like Ariconium, suggest a higher degree of organization, whether depending on private companies and capitalists or on state ownership or control. It is possible that the state never asserted its ownership of the lesser British iron mines, and left it to develop in the hands of British owners; it may have confiscated the most valuable of them. The rapid development of output in the late first century does not suggest that the industry was left entirely to the enterprise of individual labourers.

Organization in some Roman mines even went so far as the provision of pit-head baths, although no doubt such facilities were only provided in very exceptional cases. Again, the miners sometimes had to prop the galleries and leave pillars to support the roof in the workings (Davies, 1935, p. 12). In general, except in dangerous ground, the narrow galleries of ancient mines did not require propping, but when necessary timber props and shores were used; where the galleries were opened out, natural pillars of around 3 feet square were left unexcavated so as to support the roof. It is useful to note that, according to Oliver Davies (1935, pp. 18-19), in early times the Roman miner always kept to the ore once he had found it, but later, prospecting adits were used, and the Romans also drove exploratory galleries at regular intervals from a main adit. Again, in pre- and post-Roman times the ore was often obtained by means of shafts sunk at frequent intervals; this method saved timbering and the shafts were abandoned when the ore in the vicinity of the shaft became worked out. The Romans, so far as is known, avoided pitting and used orderly underground workings with frequent communications between the galleries and the surface. Some Roman mines were worked by galleries which were driven at various levels; other Roman workings do not seem to have followed any orderly arrangement.

Chapter II

THE NATURE OF METEORITES AND THE WORKING OF METEORIC IRON. ARTEFACTS OF METEORIC IRON

THE NATURE OF METEORITES

BEFORE dealing with iron which was produced in the normal way, that is, by extraction of metal from the ores of iron, we must consider another source—natural iron. Natural iron occurs in two forms, telluric and meteoric. For our study of prehistoric iron the telluric material can have little or no importance, for the only important occurrence of iron masses of possible telluric origin would appear to be in Greenland. Richardson (1934, p. 574) appears to be doubtful about the telluric iron of Greenland for he quotes Zimmer (G. F. Zimmer, 'The Use of Meteoric Iron by Primitive Man', *Journal Iron and Steel Inst.*, no. 2, 1916, p. 307) as saying, 'The specimens of telluric iron in our own national collection (if we except the dubious finds on the West coast of Greenland) can be held in the hollow of one hand; there might be enough for a few beads, but not for larger objects.' However, there is reliable evidence concerning the Greenland iron, for in 1870 Adolf Nordenskiöld found several large masses of iron at Ovifak on Disko Island. Nordenskiöld considered this iron to be of meteoric origin because it contained from 1.39 to 2.48 per cent. of nickel. Also, when polished it was supposed to exhibit a characteristic Widmanstätten structure (Rickard, 1941, pp. 58 ff.). Later research by Steenstrup and others showed that the Ovifak iron was of terrestrial origin and further analyses gave a percentage of nickel ranging from 1.74 to 2.85. It has been established that the Eskimo used this telluric iron for making knives. One mass of native iron is in the Royal Academy at Stockholm, weighing no less than 19 tons. A smaller mass of 8½ tons is in the Copenhagen museum. In a private communication dated 20 November 1953, Professor Arne Noe-Nygaard of the University Mineralogical Museum, Copenhagen, kindly informed me that the possibility evidently does not exist that the iron at Ovifak on Disko Island could be meteoric and not telluric, since the basalt containing the big iron lumps is for many miles

speckled with tiny pieces or drops of iron. In the Professor's personal opinion the iron on Disko Island has been formed through a natural reduction process in which the underlying bituminous shales have been active, setting free various hydrocarbons. In view of the evidence quoted above, we may be satisfied that the Ovifak iron is probably of telluric origin.

According to Dr. Rickard telluric iron has been detected in many localities as far apart as Arizona and Bohemia, but it is unlikely that such telluric iron was ever used by early man. Not only is it extremely rare, but much of it no doubt occurred in the form of small grains or pellets in some of the basalt formations, in which form it would have been quite useless to a prehistoric people. Indeed, Rickard mentions that the Ovifak native iron is unique in that it alone has been used by man for implemental purposes.

Turning to meteoric iron we have a considerably wider field to cover. The nature of meteorites varies within wide limits and they are classified in accordance with the proportion of stone and iron which they contain. Those who are interested in the nature and structure of meteorites are advised to consult Perry (1944) who gives a very full account, but owing to its technical nature much of the text is suited to the metallurgist rather than to the archaeologist. The following information which is of value to the general student is taken from Perry's work.

In general meteorites are classified as:

AEROLITES. These are composed of stone.

SIDEROLITES. These are composed of a mixture of stone and iron.

SIDERITES. These are composed wholly of metal.

From our point of view siderites are the most important. Again, these are subdivided into three groups—hexahedrites, octahedrites, and ataxites. In brief, the distinguishing features are:

HEXAHEDRITES. Comprised of a single structural component, kamacite (kamacite is alpha nickel-iron). Under the microscope hexahedrites generally show systems of parallel lines, known as Neumann lines, but these lines are not invariably observed. The material has a nickel content of less than 6 per cent., the proportion of nickel being uniform at around 5.5 per cent. Cobalt is apparently always present, the combined percentage ranging from about 6 to 6.5 per cent.

OCTAHEDRITES. Octahedral iron is characterized by what is known to the metallurgist as the Widmanstätten structure, a network of bands

crossing each other in two, three, or four directions. According to Dalton (1950, p. 186) octahedrites are subclassified according to the width of the kamacite plates of the Widmanstätten figures, thus:

Coarsest, plates of 2.5 mm. or wider.

Coarse, plates of 1.5 to 2 mm. in width.

Medium, plates of 0.5 to 1 mm. in width.

Fine, plates of 0.2 to 0.4 mm. in width.

Finest, plates narrower than 0.2 mm. in width.

According to Perry (1944, p. 5) the nickel content of the coarsest and coarse octahedrites is roughly 6 to 8 per cent., of medium octahedrites 7 to 9 per cent., and of fine and finest, 8 to 13 per cent. It is impossible to generalize more exactly because analyses show variations from these averages, and many of the older analyses cannot be accepted as accurate.

ATAXITES. Ataxites appear to the eye to be without structure and under the ordinary microscope show only a fine matt texture, though high magnification with central illumination reveals a rich microstructure. Ataxites may be said to fall into two sub-groups, nickel poor, and nickel rich. In the former the nickel content is approximately that of the hexahedrites; in the latter it commonly varies between about 12 and 20 per cent., with a few showing much higher percentages.

In dealing with old analyses of meteorites it appears that some caution is necessary. We may here quote Perry's remarks on this point.

In many old analyses the nickel content was greatly understated. Thus analyses of 25 irons (including many medium and fine octahedrites), of which only three were later than 1880 and 1870, show very low percentages, mostly from about 2.5 to 3.5, but fifteen of these irons analysed later showed in only one case less than 6 per cent and mostly 7 to 10 per cent. Of thirty analyses of low nickel irons (hexahedrites, coarse and coarsest octahedrites, and nickel-poor ataxites), made since Farrington's compilation (1907), not one shows less than 5.25 per cent of nickel; and of fifty-eight of the more recent analyses of all types of irons, only two show slightly less than 5 per cent, of which one is clearly erroneous. We may therefore fairly conclude that there are very few irons, if any, with less than 5 per cent of nickel.

The whole question of native iron, meteoric iron, and the nickel-bearing iron ores is somewhat obscure and further research by geologists and mineralogists would be very welcome. It is fortunate for the archaeologist that meteoric iron is, in general, easy to recognize on account of its nickel content, while the cobalt content ranges from a trace to some $3\frac{1}{2}$ per cent. (Rickard, 1932, ii, p. 846). Nickel is not a common element in terrestrial

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iron ores and, if present, it is usually in small percentage. For instance, Cuban iron ores may contain from 0·55 to 0·8 per cent. of nickel, and 1·17 to 1·51 per cent. of chromium. Hence a simple analysis to prove the nickel content will often indicate the origin of the iron. However, this cannot be taken as an invariable rule. Professor R. J. Forbes (1950, p. 380) says that there are some natural nickel-iron compounds of rare occurrence to be found in New Zealand, the Ural Mountains, and the Piedmontese Alps, also in Oregon, British Columbia, and California. But in general, he thinks that iron ores and the iron produced from them will not contain nickel, or only to a possible maximum of 2·5 per cent. On the other hand, I am indebted to Mr. P. Whitaker, Manager of Metallurgical Research at Messrs. Stewarts & Lloyds, for drawing my attention to the fact that apparently meteoric iron may also be very low in nickel and cobalt. Herr Otto Vogel of Düsseldorf (1891, p. 470) has pointed out that meteoric iron, such as that found in Hommoney Creek, North Carolina, may be quite low in nickel, cobalt, and sulphur, the analysis in percentage figures being:

Iron 93·225. Nickel 0·036. Cobalt 0·009. Manganese, Trace. Silicon 0·501. Phosphorus, Trace. Sulphur 0·543. Carbon 4·765.

The following figures show that a wide range of analysis of the separate elements contained in meteoric iron has been recorded:

Sulphur 0·08 to 5 per cent.	Phosphorus 0·08 to 1·5 per cent.
Nickel 0·07 to 60 „	Cobalt None to 3 „
Manganese. Tr. to 4 „	Silicon 0·02 to 0·8 „

With such wide variations in composition, under certain conditions one would expect that there would be difficulty in distinguishing the nature of the iron. Later, we shall see that such difficulty has in fact occurred.

Observed falls of meteorites are not very frequent, and for this reason it has sometimes been supposed that the quantity of meteoric iron available would have been very small. Of course this is true if the comparison be made with the enormous quantity of iron ores in the world, but when we consider the length of time over which meteorites have been falling, the quantity cannot have been negligible. In the British Museum collections alone there are probably several hundred meteorites which have fallen within the last hundred years, and these can be only a fraction of those which fell all over the world during the same period. Concerning the size of meteorites, they vary from large masses weighing many tons,

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down to small pellets or even dust. Dr. Rickard (1941, pp. 58 ff.) mentions the following large meteorites. Three meteorites examined by the American explorer Robert Peary at Melville Bay in 1894 were named by the Eskimo the Tent (of $36\frac{1}{2}$ short tons in weight), the Woman (3 tons), and the Dog (966 pounds). The Woman meteorite had been much used by the Eskimo so that it originally may have been twice as heavy. In 1913 a fourth meteorite of some 8 tons in weight was recorded from about ten miles north-east of the other three on the Cape York promontory. Analyses gave the composition of the three meteorites as:

Iron 91.47 per cent. Nickel 7.78. Cobalt 0.53. Copper 0.016. Phosphorus 0.188 per cent.

The Rodeo meteorite, discovered in 1852 on the Nazas River in Mexico, weighed 97 lb., and was used for many years as an anvil. It contained 8.79 per cent. of nickel with 0.28 per cent. of cobalt. At Descubidora, in Mexico, a meteorite was found which weighed 1,265 lb. and contained 8.05 per cent. of nickel, and at Catorze in Mexico there was a meteorite of 92 lb. In Argentina, the Otumpa meteorite originally weighed 8 tons and had a nickel content of 5.11 per cent. What Rickard states to be the largest of all known meteorites is that of Hoba in south-west Africa. The estimated original weight was approximately 88 tons. The nickel content is high, 16.24 to 16.76 per cent., cobalt 0.76, and copper 0.03 per cent. In Europe and Asia the recording of meteorites does not seem to have been at all complete. Wainwright (1936, p. 6) remarks upon some of the more famous ones and others are quoted by Rickard in his paper on the use of meteoric iron. Others from Europe and Asia are given in Table I, which has been extracted from Zimmer's very complete list of the known falls of meteorites (see p. 36).

There can be little doubt that a great number of meteorites have never been observed or found and therefore remain unrecorded.¹ It has been estimated, although any such estimate can only be very approximate indeed, that between 100 and 400 meteorites may fall every year. We cannot, of course, estimate what proportion of the total number of meteorites which fall contains a useful quantity of nickel-iron. The known finds of meteoric iron are related in some measure to population density, and

¹ In the *Illustrated London News* of 8 August 1953 it is reported that two large meteorites were being studied by the Special Meteorite Committee of the U.S.S.R. It is stated that the Tunguska meteorite fell in Central Siberia in 1908, but was not studied until after the October revolution. In 1947 a huge meteorite burst in the air in the Sikhote-Alin district north of Vladivostok and fell as a shower. One hundred and twelve craters were found, yielding fragments varying in size from 1 ton 14 cwt. to one of 0.18 grams.

a similar factor may well have influenced the utilization of the metal. Certainly, there is an apparent scarcity of meteorites in the Old World.

THE WORKING OF METEORIC IRON

Before discussing such meteoric iron as is known from prehistoric contexts it is well to take another side of the question into consideration, that is, the difficulty or otherwise of working meteoric iron. While this iron cannot be said to be an easy material to make use of, it has been proved that some use was made of it by prehistoric man, and some examples of its use by modern primitive people are of value in showing how the iron was worked. With primitive tools it would be very difficult, if not impossible, to obtain or work pieces of meteoric iron of any considerable size. In Greenland the Eskimo had iron knives, but the blades were not as a rule made in one continuous piece as in a modern knife, but consisted of a number of small segments of iron set in a groove formed in a handle of bone or ivory (Fig. 2, and pp. 177-9). Concerning the actual process of detaching small pieces of iron from the parent meteorite, the Eskimo hammered narrow edges or ridges of the mass with stone hammers until small flakes, of about 1 centimetre in diameter, were detached. The time and labour required must have been enormous; indeed, Rickard mentions that the 'Woman' meteorite, which had been used by many generations of Eskimo, had accumulated around it a pile of stones, some 18 to 20 feet in height, which had been used as hammers. Analyses have proved that the North American Indians also used meteoric iron; tools and ornaments were found in the Turner mounds in Ohio. Copper tools would be of little help in detaching pieces of iron from a large meteorite, but apparently copper was sometimes used for wedges in an endeavour to split off fragments from a large mass. Such was the case with the previously mentioned Descrubidora meteorite where a broken copper

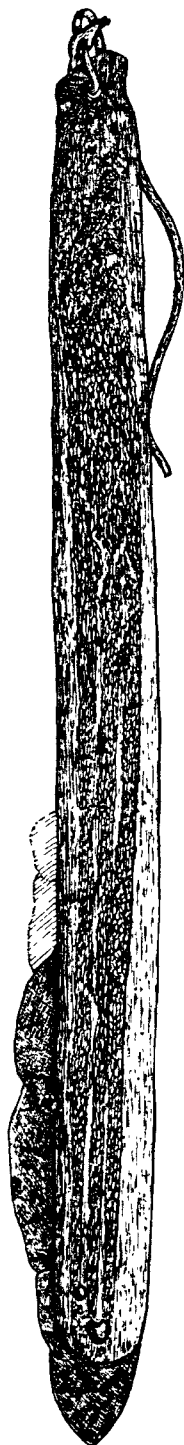


FIG. 2. Eskimo knife of small pieces of meteoric iron set in walrus ivory, collected by Captain (later Sir) John Ross, R.N., on 13 August 1818 from Prince Regent's Bay, North Greenland, now in the Pitt Rivers Museum. (See pp. 177-9.)

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chisel was found wedged in a gap in the meteorite. Also a chisel of native copper was found stuck in a cavity of the Catorze meteorite. Smaller meteorites would no doubt have proved more suitable to the methods available to prehistoric or primitive man.

As Rickard (1941, p. 62) says:

Some siderolites, partly stone and partly iron, such as those of L'Aigle and Estherville, consist of pieces of iron enclosed within a stony matrix, commonly a hypersthene-olivine complex, from which the useful metal can be detached easily by hammering. In these stone-iron masses, known as pallasites, the iron is embedded like raisins in a pudding, and can be detached with comparative ease. Occasionally the stony matrix has become so much decomposed and eroded as to cause projecting points of iron to become detachable. These thorny masses of rock would attract the attention of primitive man. A loose fragment might yield a piece of flat iron already pointed and ready for use.

Some confusion has been caused by statements to the effect that meteoric iron is not malleable. Such general statements are not correct, and while meteoric iron may not be so malleable as a modern mild steel, there is no technical reason for doubting that it is often malleable. As Zimmer has pointed out, the nickel which is always present in meteoric iron cannot impair its malleability because nickel itself, or nickel as an alloy with iron, is malleable. Zimmer says:

It is well known that the artificial alloy of iron and nickel (nickel steel) combines the ductility of homogeneous iron (flux iron) with the advantages of hard steel, and is the best kind of modern iron. Wolf, who first introduced artificial nickel-steel, brought it on the market as 'Meteor Steel'. The addition of only one per cent. of nickel renders the iron hard and tough, up to three per cent. improves the alloy (modern armour plates contain, by the way, $3\frac{1}{4}$ per cent. of nickel, and do not crack even when deeply penetrated by a projectile), and with more than 9 per cent. the nature of the alloy gradually changes from that of nickel-iron into that of nickel.¹

On the other hand, there is no doubt that some meteoric iron is exceedingly tough and difficult to cut. Some interesting research by new methods upon the microhardness testing of meteorites has recently been carried out by F. K. Dalton (1950, pp. 1-11 and 185-95; 1951, pp. 77-78) who, when cutting a specimen which had fallen near the Canyon Diablo crater in Arizona, destroyed eight special hacksaw blades where two should have sufficed. This agreed with Foote's experience in 1891, when he destroyed several chisels and a grindstone in his attempts to cut some of these meteorites. After Dalton's first specimen was polished,

¹ See pages 177-9.

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small areas with a tarnished appearance could be seen spread over the section. These small areas were found to be extremely hard. Upon this point Dalton remarks:

The hexahedrites are quite consistent at about 180 on the Knoop scale. Kamacite in the octahedrites, having higher nickel, has hardness of approximately 260 while the still higher nickel-iron of taenite borders in octahedrites is much harder, ranging from 430 to 750. These materials may be compared with well known artificial steels, as follows, and it will then be seen that the natural steels are of very high grade indeed.

Structural Steel	170	} Knoop hardness.
Spring Steel	290	
Tool Steel, annealed	305	

Dalton also found inclusions of great hardness in meteorites. For instance, schreibersite in Canyon Diablo specimens ranged from 1100 to 1360 Knoop hardness. Harder still were carbonados, or black diamonds, discovered on several occasions. In view of these results, the difficulty experienced in cutting certain meteorites is explained, and specimens containing inclusions of such extreme hardness must have been valueless to prehistoric or primitive man.

If a piece of meteoric iron of suitable size and shape was not found ready to hand, it would be necessary to forge the iron. Here difficulty may well arise. As we have seen, there is no doubt that the nickel-iron obtained from meteorites is of much superior quality and strength as compared with primitive wrought iron obtained by direct smelting. On the other hand, the nickel-iron would almost certainly be more difficult to forge. Richardson (1934, p. 574) made certain experiments in the forging of meteoric iron which point to the process as not being an easy one. The experiments were carried out on eleven small pieces from the San Angelo meteorite, a medium octahedrite, of which the analysis was:

Iron 91.96 per cent. Nickel 7.86. Carbon—Manganese—Silicon 0.011.
Phosphorus 0.099. Sulphur 0.032. Cobalt—Copper 0.04 per cent.

Hardness, approximately 250 Brinell.

Richardson first experimented with melting of the material, but to us melting is not of interest in connexion with the early use of meteoric iron, for it could never have been carried out owing to the high temperatures required. In the forging experiment a piece weighing 66 grams was heated to a medium cherry red (1,250° F.), then reheated to light cherry (1,550° F.), and to salmon (1,650° F.). It was then forged on an anvil with a ballpene hammer. The iron was found to be ductile and yielding

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under the hammer, but in forging it showed a tendency to open up along the boundaries of the kamacite plates. With the temperature increased to a welding heat ($2,200^{\circ}$ F.), it was found that the metal would not weld or flow into a solid piece because of cracking along the cleavage planes. Concerning these experiments Richardson says that it is perhaps reasonable to conclude, if conclusions are possible from a single experiment, that most of the hexahedrites and many of the medium octahedrites were beyond the simple technique of primitive man. Long prior to Richardson's experiments, Dr. Beck (1892) had experimented with a piece of the meteoric fall from Toluca, Mexico. Beck's first experiment was unsatisfactory for he found that, while the material was ductile when cold, it would not adhere under welding heat and broke up under the hammer. In a second and later experiment Dr. Beck obtained a satisfactory result. He found that the iron worked well under the hammer at a moderate welding heat and the piece was forged into the form of a small rod, and this rod of meteoric iron was welded to a similar rod made of ordinary iron, a sound weld being obtained. Beck attributed the failure of his first experiment to penetration by moisture along the crystalline surfaces of the meteoric iron so that thin films of rust prevented adherence when an attempt was made to weld the material. Zimmer (1916, pp. 315-16) also quotes experiments by other workers which confirm that a high proportion of meteoric iron is both malleable and may also be welded.

ARTEFACTS OF METEORIC IRON

We may now examine what is known of meteoric iron artefacts in prehistoric times. Unfortunately the list is a short one, and is no doubt incomplete. After all, as the Ėskimo worked and used meteoric iron with very primitive equipment, we cannot deny that prehistoric man may well have done the same thing, indeed we have proof that this was so. First, we have the iron beads which Wainwright (1936, p. 7) found at Gerzah in Egypt, about fifty miles to the south of Cairo. The beads were in two groups, roughly contemporary at S.D. 60-63, and analysis showed the metal to contain 7.5 per cent. of nickel, clearly proving their meteoric origin. In the XVIIIth-dynasty tomb of Tutankhamun were several iron objects, a dagger, miniature head-rest, an amuletic eye, and sixteen miniature implements (Lucas, 1948, p. 272). We cannot tell if this iron is of meteoric origin as an analysis has not yet been made; in view of the advanced date, and the fact that Lucas mentions that the head-rest has been badly welded, we take the view that this iron

is of terrestrial origin and was an import into Egypt. Certainly of meteoric origin is a small amulet which has a silver head and an iron blade. This amulet is from Deir el Bahari, in Egypt, and is of the XIth dynasty. The iron blade was analysed by Professor Desch and found to contain 10 per cent. of nickel (Lucas 1948, p. 271, and Desch, RBA 1936, p. 309). Several other finds of early iron in Egypt have often been quoted, but as there appears to be considerable doubt about their origin and dating, it would be unwise to include them in our list.

In one of the Royal Tombs of Ur in Mesopotamia, Sir Leonard Woolley found some fragments of iron (Peake, 1933, p. 641, and Desch, 1928). These fragments contained 10.9 per cent. of nickel, and were therefore of meteoric origin. There are two objects from Treasure L of Troy II or III, but doubt was expressed whether these pieces were really iron, and analyses were therefore carried out in the Königliche geologischen Landesanstalt und Bergakademie in Berlin, whose director, Professor Dr. Finkener, was of the opinion that the pieces were not metallic iron, but a mineral ore. The analyses (Dörpfeld, 1902, p. 423) show a nickel content of 2.44 and 3.91 per cent., and do not appear suitable to derive from any of the ordinary iron ores. On the other hand, the analyses do not appear to be those of meteoric iron. Hence, it is unwise to consider that the Treasure L find is of meteoric origin. It is also significant that artefacts of relatively low nickel iron have been recorded from period III of Alaca Hüyük. These are an iron pin with gold-plated head, Al/a, MC 34, and a fragment of a crescent plaque, Al/a, MC 33. Both objects have been analysed with the following results (Koşay, 1944, p. 189):

Al/a. MC 34. Pin.

	72.20 per cent.
	3.44 "
	4.69 "
Total	80.33 "

By calculation

94.92 per cent. Fe.
5.08 " Ni.

Al/a. MC 33. Plaque.

76.30 per cent.	Fe ₂ O ₃
3.06 "	NiO.
0.99 "	CaO.
2.65 "	Al ₂ O ₃
Total 83.00 "	

By calculation

95.7 per cent. Fe.
4.3 " Ni.

In view of the above figures it is possible that a low-nickel meteoric iron is here in question. Przeworski (1939, p. 143) says that there were early finds of meteoric iron from a Tholos near Platamos, and at Mavro Spelio, but he does not comment on the nickel content. Peake (1933, p. 641) mentions that in 1927 a cube of iron was discovered at Knossos

in Crete in a Middle Minoan grave dating from about 1800 B.C. It had evidently been regarded as a precious object, and is likely to be of meteoric iron. The same is probably true of the iron finger-ring, believed to date from 1550 B.C., found at Pylos in the Peloponnesus.

In the case of artefacts of the lower nickel ranges, unless there is careful metallographic examination as well as the analyses, a certain confusion would appear possible because of the mineral pyrrhotite (an iron mineral which occurs in grains or massive form impregnating metamorphic or crystalline rocks). For example, concerning the important Ras Shamra axe (see my p. 63), the analyst Leon Brun said (Schaeffer, 1939, p. 110): 'The axe-body is steeled iron. The very oxidized iron in the mass contained no trace of manganese. Also no chromium, copper, tellurium, or vanadium, were found.' At first Brun thought the iron was meteoric, but the analysis and the microscopic examination showed that the iron was probably made from pyrrhotite, a magnetic material containing from 2 to 5 per cent. of nickel. Examination of the impurities supported this opinion. On the other hand, Dr. Witter did not agree with this view. In his opinion (1942*b*, p. 55) pyrrhotite is a magnetic pyrites which contain about 60 per cent. of iron and about 40 per cent. of sulphur. Since many magnetic pyrites contain some nickel (from a weak percentage up to 5.6 per cent.), this mineral is used to obtain nickel. Up to the present this sulphur-iron ore has not been used for the production of iron, and in prehistoric times that would have been quite impossible. Witter thinks that the iron used to make the Ras Shamra axe was meteoric, and from an ataxite without structure, this class of meteoric iron being difficult to distinguish from terrestrial iron. Meteoric iron of similar chemical composition to the Ras Shamra specimen has been found elsewhere.

Here we find two undoubted authorities in conflict concerning a fundamental matter. While we must agree with Witter that it is highly unlikely that prehistoric iron smelters could have made use of the mineral pyrrhotite, unless the whole matter be re-examined we must favour the opinion of the scientist who carried out the research, especially since he was well aware of the possibility that meteoric iron might be in question.

Lower in the nickel range, there is the strange case of the British currency bar examined half a century ago by Professor Gowland (1903-5, p. 194). Two bars, designated *A* and *B*, were examined with the following results:

						<i>Bar A</i>	<i>Bar B</i>
Carbon	trace	0.08
Silicon	0.09	0.02

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				<i>Bar A</i>	<i>Bar B</i>
Phosphorus	.	.	.	0.69	0.35
Manganese	.	.	.	nil	nil
Nickel	.	.	.	0.23	nil

In the report it is stated that 'Sections of bar *A* presented no slag patches such as are universally found in wrought iron, but closely resembled meteoric iron.' Again, 'Bar *A* has hence apparently been made from meteoric iron. The use of meteoric iron must, however, have been quite exceptional.'

While one hesitates to doubt the statement of so eminent an authority as the late Professor Gowland, it is difficult to accept that bar *A* was in fact forged from a meteorite. First, ordinary bloomery iron must have been relatively common when these currency bars were made. Again, in England it may be exceptional to find a meteorite large enough to make a substantial bar, although the Rowton, Shropshire, meteorite weighed 3.87 kg., but here the nickel content was normal at 8.56 per cent. Secondly, the nickel content of the bar at 0.23 per cent. is low for meteoric iron in general. On the other hand, iron with similar nickel content is not unknown. There is the piece of iron from the Saalburg in Germany which contained 0.242 per cent. of nickel (Weiershausen, 1939, p. 227).¹ There may well be other examples of a like nature although, in general, an appreciable nickel content is decidedly rare in primitive iron.

As we have mentioned, the list of authenticated objects of meteoric iron is all too short. Writing as long ago as 1912 (p. 277), Professor Gowland held the view that native iron, whether of meteoric or telluric origin, can have played no part in the rise and development of the Iron Age. In view of the rarity of archaeologically attested specimens of meteoric iron it is difficult to know whether, or to what extent, meteoric iron may have influenced the discovery or development of smelted iron, but, as Wainwright (1936, p. 5) has pointed out, man must have first come to know of iron through meteorites.

We must await further discoveries and analyses of very early iron before we can form an opinion of the degree to which such iron was used in the Old World. From the foregoing it will be seen that, while the available evidence is scanty, it is clear that a certain use was made of meteoric iron during prehistoric times. We have also ample evidence for

¹ See also the spear from Deve Hüyük, Syria, dating around 600-500 B.C., which showed 0.32 per cent. of nickel. See p. 137.

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the use of meteoric iron by modern primitive peoples in the New World. In prehistoric times meteoric iron may well have been the first iron known and used, but such knowledge and use can never have constituted anything remotely approaching an Iron Age in any part of the Old World. As we have already mentioned, there were various factors which must have limited the use of meteoric iron. First, there was the difficulty of finding the iron, and in obtaining a piece of suitable size and shape. Having found the iron, there was next the possible difficulty of forging it, but here we must remember that the meteoric iron (at least in certain cases), could have been shaped by means of a measure of cold-working and grinding. Prehistoric people had a long tradition of stone-grinding behind them, and they would not have been slow in applying the grinding technique to the new metal. Again, an even greater limitation must have been caused by the relative scarcity of meteorites, and by the fact that the major quantity most likely remained unrecognized.

TABLE I

Meteorites—Europe and Asia

Extract from Zimmer's table. J. Iron and Steel Inst. xciv. n. 2 (1916), 324-35.

Name	Date of fall or find	Original weight in kilos.	Per cent.		Remarks
			Iron	Nickel	
	26 May				
AGRAM. Hungary . . .	1751	48.75	96.5	3.5	Malleable.
ALT-BIELA. Austria . . .	1898	3.9	85.34	12.89	..
ARVA. Hungary . . .	1840	1,700	90.18	3.09	Nearly as hard as steel; yet malleable.
AUGUSTINOVKA. Russia . . .	1890	400	91.91	7.7	Malleable.
	31 Mar.				
AVCE (near Trieste. Austria) . . .	1908	1.23	..	..	..
BISCHTÜBE. Asiatic Russia . . .	1888	48.75	91.52	7.12	Malleable.
BITBURG. Prussia . . .	1802	1,650 about	..	..	Ductile, even cold.
BOHUMILITZ. Bohemia . . .	1829	47 about	92.47	5.67	Malleable, close and firm.
*BRAHIN. Russia . . .	1810	100 about	88.96	11.04	Malleable.
	14 July				
BRAUNAU. Bohemia . . .	1847	40.71	91.88	5.52	Dense, tough, and ductile.
*BREITENBACH. Bohemia . . .	1751	10.5	90.43	9.28	Malleable.
ELBOGEN. Bohemia . . .	1400	107	89.9	8.43	Malleable.
FINMARKEN. Norway . . .	1902	77.5	Resembles the Pallas iron in every way (Cohn), therefore malleable.

Those marked * are siderolites.

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Name	Date of fall or find	Original weight in kilos.	Per cent.		Remarks
			Iron	Nickel	
FISTERHÖLZELRICS. Bohemia . .	1909	..	..	..	Malleable.
*HAINHOLZ. Prussia . . .	1856	16.5	..	..	Non-malleable.
KODAIKANAL. Madras . . .	1898	15.87	..	..	..
LA CAILLE. France. . . .	1828	575	92.5	5.9	Malleable.
LENARTO. Hungary	1814	108.64	90.15	6.55	Malleable.
RAFRÜTI. Switzerland . . .	1886	18.5	89.87	9.54	Fine-grained iron.
RITTERSGRÜN. Saxony . . .	1833	86.5	..	..	Non-malleable.
	20 April				
ROWTON. Shropshire	1876	3.87	91.25	8.58	Malleable.
SÃO JULIÃO DE MOREIRA. Portu- gal	1883	162 over	89.39	8.27	Malleable.
SAREPTA. Russia	1854	13.33	95.94	2.66	Malleable.
SCHWETZ. Prussia	1850	21.64	92.01	7.55	Malleable, wrought speci- men in Göttingen Mu- seum.
SEELÄSGEN. Prussia	1847	102	92.33	6.23	Soft and malleable.
SHIROHAGI. Japan	1890	22.7	93.52	5.92	Malleable. Sword was wrought from a frag- ment.
SSYROMOLOTOVO. Asiatic Russia .	1873	220	92.64	7.1	Very soft and malleable.
*STEINBACH. Saxony	1751	1,000 about	..	..	..
TABARZ. Germany	1854	0.05	92.76	5.69	Malleable.
TANOKAMI. Japan	1858	172.87	90.11	8.56	Malleable.
TOUBIL RIVER. Asiatic Russia .	1891	21.96	95.14	3.53	Malleable.
TOUBIL. W. Siberia. Russia . .	1891	22	95.18	3.88	Malleable.
TULA. Russia	1846	246	93.5	2.5	Malleable, mostly utilized.
*VERAMIN. Persia	May 1880	51.4	92.06	6.96	..
VERKHNE-DNIEPROVSK. Russia .	1876	0.5	..	..	..
VERKHNE-UDINSK. Asiatic Russia	1854	18.5	91.02	7.31	Malleable
	1 June				
MARJALAHTI (Viborg. Finland).	1902	44.8	92.28	7.13	Malleable.
*MORRADAL. Norway	1892	2.75	79.67	18.77	Malleable.
MUONIONALUSTA. Sweden . . .	1906	7.53	91.1	8.02	..
NAGY-VAZSONY. Hungary . . .	1890	1.89	..	..	Malleable.
	23 Jan.				
NEDAGOLLA. Madras	1870	4.54	92.61	6.2	Malleable.
NEJED. Central Arabia	1863	59.8	91.04	7.4	Soft and easily cut with a hack-saw.
NENNTMANNSDORF. Saxony . .	1872	12	94.5	5.31	Soft malleable iron.
OBERNKIRCHEN. Germany . . .	1863	41	92.45	7.55	Soft and ductile.
	7 April				
OKANO. Japan	1904	4.73	94.85	4.44	..
*PALLAS IRON. Asiatic Russia .	1749	750	..	..	Malleable.
*PAYLODAR. Asiatic Russia . .	1885	6	..	..	Malleable.
PETROPAYLOVSK. Asiatic Russia .	Pre- historic	7.16	97.29	2.07	Malleable.

Of a total of 287 falls which are given in the complete table, 250 are malleable, 5 non-malleable, and 32 undetermined.

Chapter III

THE SMELTING PROCESS AND THE MECHANICAL PROPERTIES OF IRON

THE SMELTING PROCESS

WE may now consider how iron is obtained from the ores which are so abundantly distributed all over the world. Although iron was known and obtained in small quantity from meteorites, it was not until the discovery was made of how to win iron from the ores that the metal could be obtained cheaply and in any quantity desired; in this matter we must endeavour to give some idea of what the smelting process means, and also to avoid confusion between ancient and modern methods. As Straker (1931, p. 16) has so clearly pointed out, there may be said to be two processes, direct and indirect. The direct or bloomery process was that used in general by prehistoric and primitive man. Here the iron is produced in small quantity, and by one operation a sponge iron is obtained, which after simple treatment may be at once forged into the desired tools and weapons. The indirect process, now associated with the blast furnace, produces cast iron and is a complex and recent development of iron founding. Hence, in this work we are concerned almost entirely with the original bloomery or direct method.

In the actual reduction, or smelting, of the iron ore, a chemical change is involved. For the production of iron by the direct process the oxides of iron, such as haematite, limonite, and magnitite, would be suitable. Prehistoric man would not have been able to make use of the sulphide ores.¹ Iron pyrites is not suitable for iron smelting; only in modern practice is some iron obtained from pyrites as a product in the manufacture of sulphuric acid. In the reduction of an oxide ore the chief consideration is to rob the ore of its oxygen and so to obtain metallic iron. If the fuel used in the reduction furnace be charcoal, the carbon of the fuel will combine with the oxygen of the ore and metallic iron is released.

It is practically certain that the fuel used by the first iron smelters was charcoal, hence in a simple reduction furnace the carbon of the charcoal will burn to carbon monoxide, and this gas will take oxygen from the ore

¹ But the work of Professor Pittioni (1951) and others would point to the possibility that the sulphide ores of copper were worked in Austria at least by the late Bronze Age.

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to form carbon dioxide. However, a certain balance must be preserved, as Professor Read has stated (1934, p. 384):

No amount of heat alone will reduce a mixture of iron oxide and iron sulphide to usable metal. When iron sulphide alters to oxide in nature, the reaction commonly proceeds to the end, and a natural mixture of iron sulphide and iron oxide is much less common than a natural mixture of sulphide and oxidized ores of copper and lead. Furthermore, iron sulphide is so soluble in the metal and makes it so brittle that usable iron could not be produced in this way, even if it were otherwise possible. To produce usable iron the metallurgist must employ only iron oxide together with both heat and carbon, the latter performing an essential chemical function in the operation. There must be a sufficient excess of carbon so it will burn to carbon monoxide, not dioxide; whenever the ratio of dioxide to monoxide rises above a number that varies with temperature, metallic iron re-oxidizes. The primitive metallurgist never understood this role of carbon in iron production; he merely knew that if he did things in a certain way he got a certain result. All the early attempts to produce metal from iron oxide must have ended in failure until it was empirically discovered that sufficient excess of carbon must be present to keep the carbon dioxide concentration down to where the reduction of iron oxide to iron can take place.

Within reasonable limits, a high furnace is more efficient for smelting than a low one; the reason being that the chimney effect of the high furnace gives the carbon monoxide gas a better opportunity to act upon the ore. Also, the success of the primitive smelting operation largely depends on a charcoal fuel and on the exclusion of oxygen from the ore while it is being smelted. The temperature at which reduction takes place has an important bearing on the smelting process. In general, reduction may be obtained at temperatures as low as 700 to 800° C., but as Richardson (1934, p. 577) has pointed out, when iron oxide is reduced at temperatures below 900° C., a dark grey and very porous substance is formed which would be impossible to forge. With temperatures in the range of 1,000° to 1,050° C., the result of the smelt will be a loosely coherent mass which would be exceedingly difficult, if indeed possible, to forge. Not until the temperature range is increased to 1,100–1,150° C. does the iron begin to flow together forming a pasty, semi-fused, and somewhat porous mass; this is a bloom, and it may be worked and forged so as to give the well-known wrought iron of early times.

From the above considerations it follows that, if we are to obtain a useful bloom of iron, sufficient temperature in the furnace and a good reducing atmosphere with the exclusion of oxygen from the ore are essentials. Again, the primitive reduction process was wasteful in material.

Much charcoal fuel was used, and much of the iron was lost in the slag. Forbes (1950, p. 393) mentions that in furnaces of the type found near Tarxdorf, in the Tyrol, Schmaltal, a semi-fused bloom of about 50 lb. in weight demanded the consumption of some 200 lb. of charcoal, plus another 25 lb. of charcoal for the subsequent forging operation. Also, starting with a charge of about 300 lb. of ore the founder would only obtain something like 25 lb. of fairly good iron. Concerning the loss of iron to the slag, Forbes points out that one of the main difficulties is the gangue of the ore. The gangue of an iron ore is largely siliceous, and the silica of the gangue combines in the furnace with part of the ferrous oxide of the ore to form a fusible slag. In the primitive direct process the slag does not separate easily, and a high proportion of the iron is lost in the slag. In modern practice lime is usually added to the charge as a flux. The flux renders the slag far more fusible, so that it readily separates from the iron. Hence, productive efficiency is greatly increased by the selection and use of a suitable flux. It is interesting to note that so rich in iron were some of the ancient slags that they have been reworked with profit in recent times.

FLUXES

As the matter is of such importance in the smelting process, we must endeavour to make clear the nature and use of a flux for iron smelting. A furnace charge of ore and fuel will usually contain more or less extraneous matter. To separate and get rid of this extraneous matter certain materials known as fluxes must be added to the furnace charge so as to form a slag. To give an idea of the various fluxes which will serve the purpose, we cannot do better than quote the principal earthy fluxes, as used in modern practice, given by Professor Roberts Austen (Austen, 1923, p. 295):

- (a) Lime, which acts as a powerful base for removing silica. Lime is used in a pure state or as carbonate. Limestone is largely used in iron smelting as most iron ores contain an excess of silica. Dolomite, the carbonate of lime and magnesia, is specially useful.
- (b) Fluorspar (calcium fluoride), which is a useful flux for ores containing silica, barytes, or gypsum. With the two latter it easily fuses. It is also used in the open-hearth furnace to increase the fluidity of the slags and for the removal of sulphur.
- (c) Barytes, which acts as a powerful base and it is a good sulphurising agent. In the concentration of nickel speise, the copper present with the speise is removed and a regulus formed.

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- (d) Alumina-bearing rocks, such as clay-slate, are used in smelting ores which are very rich in lime, but as a rule the charge is so mixed that argillaceous and calcareous ores are present in suitable proportions.
- (e) Siliceous materials, such as quartz, natural silicates, siliceous slags, are used when the ores contain an excess of basic materials that have to be removed.
- (f) Oxides and carbonates of iron, basic iron slags, &c., are used in the smelting of siliceous ores, especially of lead and copper.

From the above it will be seen that, in modern practice, the flux may be adjusted to the nature of the charge with considerable accuracy. For primitive working, some archaeologists quote the use of lime as a flux, and indeed one would consider lime as the flux most probably used at an early stage in the evolution of smelting. May (1904, p. 13), however, did not consider that it was in use at Warrington even during Roman times. In his view,

the result of many analyses of iron and slag from the small reverberatory furnaces, sow kilns and bloomeries of the Roman period proves that lime was not used as a flux to extract pure iron from the ore as in modern practice. The Roman blacksmith (Faber Ferrius) chose the easier method of conveying the red-hot spongy mass to the anvil with a long pair of tongs and expelling the last dregs of impurity by repeated blows of a heavy hammer. The sparks which fly in all directions from the anvil when a blacksmith is at work consist of impure iron and slag, and when the sparks cease to fly the workman knows that his iron has 'come to nature' and can be converted into steel by cementation and tempering.

SLAGS

The refuse from the smelting process are known as slags, or, expressed in more technical language (Austen, 1923, p. 296), 'the silicates formed in metallurgical processes by the combination of silica with the earths and metallic oxides are termed slags'.

According to Roberts Austen, the bases (mostly combined with silica) which are formed in silicate slags are lime, alumina, magnesia, rarely ferric and manganic oxides, ferrous oxide, &c. Further, there are certain oxides and earths, such as those of zinc oxide and alumina which interfere with the fluidity of the slag and would therefore hinder the primitive smelter. Perhaps a clearer definition of a slag is that given by Alexander and Street (1946, p. 187): 'glass-like compounds of comparatively low melting point, formed during smelting when earthy matter contained in an ore is acted on by a flux. If the earthy matter were not deliberately so converted into slag it would clog the furnace with unmelted lumps. The

THE SMELTING PROCESS AND MECHANICAL PROPERTIES OF IRON fusibility and comparatively low density of the slag provides a means by which it may be separated from the liquid metal.'

With our modern methods of iron production, slags with varying physical and chemical properties are produced as furnace refuse, some of which is used commercially. In prehistoric times no use was made of the slag. In the Weald of Kent, however, the Romans did make use of slag for road foundations. Modern uses are for railway ballast, tar macadam, cement, fertilizers, and slag wool for heat insulation. As the refuse or slag from an iron-smelting furnace is practically indestructible, the examination of such slag is useful in various ways. First, it often leads to the discovery of the smelting site which would otherwise possibly never be found. Secondly, the slag gives us a good indication of the ore used and of the smelting process in force. Further, analysis and examination of the slag will, in many cases, allow the approximate period of the smelting operations to be determined. Certainly prehistoric or Roman slag may be differentiated from the modern slags. It is, however, dangerous to attempt a chronological dating of slags by inspection of their external quality. The quality and appearance of a slag depend upon various factors of the furnace technique. Many furnaces of the Middle Ages have produced slag similar to that produced by prehistoric furnaces.

Straker has shown the value of such study by means of analysis and micro-sections of the Wealden iron slags. The following table (Straker, 1931, p. 94) is of particular interest in showing the composition of a bloomery slag or cinder from the 'ox-bone', North Wood, Guestling, and of the extreme variations of analyses from other localities.

<i>North Wood</i>	<i>Per cent.</i>	<i>Others (per cent.)</i>
Silica	32.4	29 to 38
Alumina	7.1	2 to 7
Iron Oxide	53.4	31 to 59
Manganese oxide	1.8	2 to 12
Lime	3.2	2 to 8
Magnesia	1.3	1 to 3

The limits given by Straker can be exceeded, as witness the analysis of a prehistoric or Roman slag from the excavations at Blewburton Hill, Berkshire, in May 1950. The analysis was made for the Royal Anthropological Institute, Ancient Mining and Metallurgy Committee, by Messrs. Alfred Herbert, Coventry.

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Silica (SiO_2). 10.15 per cent. Phosphorus Pentoxide (P_2O_5). 0.96 per cent.

Sulphuric Anhydride (SO_3). 0.08 per cent. Lime (CaO). 5.70 per cent.

Magnesia (MgO). 0.40 per cent. Alumina (Al_2O_3). 1.10 per cent.

Manganous oxide (MnO). Traces. Titanium Dioxide (TiO_2) Traces.

Copper, nickel, zinc, cobalt. Not detected.

Ferrous iron (calculated to FeO). 61.54 per cent.

Ferric iron (calculated to Fe_2O_3). 19.69 per cent.

Total iron (calculated to Fe). 61.79 per cent.

The sample is slightly magnetic.

During the course of excavating Roman iron furnaces and forges at Wilderspool and Stockton Heath, near Warrington, T. May devoted considerable attention to the iron slags (1904, pp. 20 ff.). Three of these analyses are given below:

Slag from Iron Furnace I. Wilderspool

Silica	.	.	.	.	59.65
Alumina	.	.	.	.	13.41
Manganic oxide	.	.	.	.	0.20
Ferrous oxide	.	.	.	.	18.14
Ferric oxide	.	.	.	.	3.84
Phosphoric acid	.	.	.	.	0.48
Iron pyrites	.	.	.	.	1.46
Carbonaceous matter and moisture	.	.	.	.	3.18
					<hr/> 100.36

Slag from Hearth II. Wilderspool

Ferrous oxide	.	.	.	.	51.80
Ferric oxide	.	.	.	.	6.73
Manganese.	.	.	.	.	0.26
Alumina	.	.	.	.	5.20
Lime	.	.	.	.	3.00
Magnesia	.	.	.	.	1.17
Silica	.	.	.	.	28.07
Phosphoric acid	.	.	.	.	0.43
Sulphuric acid	.	.	.	.	0.19
Organic matter and water	.	.	.	.	1.70
					<hr/> 98.55

From Refining Furnace I

A small globule of cinder from the wall of the furnace, underneath the calcined lining.

Silica	73.800
Ferrous oxide	17.5
Ferric oxide	1.2

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Alumina	1·7
Magnesia	0·55
Phosphoric acid	0·724
Sulphuric acid	1·650
Alkalis, &c.	2·876

Mr. Ruddock (Public Analyst, Warrington), inferred that such a slag as this would be obtained by reducing an ore containing appreciable quantities of phosphorus and sulphur. May also remarked:

(1) The composition of the slags varied from about 80 per cent. of silicate of alumina and other impurities and 20 per cent. of oxides of iron to about 75 per cent. of the latter and 25 of impurities.

(2) The small proportion of lime present in the slags shows that it was merely an accidental impurity, and was not added intentionally as a flux.

(3) The quantity of alumina in the slag and a large number of specimens prove that clay-band ores were principally used.

(4) Pure silica in the form of pounded white quartz pebbles appears to have been added as a flux (for the haematite ores), the black glassy specimens of slag when pounded being found under the microscope to contain a large proportion of these white particles, with occasional lumps half an inch in diameter.

These few analyses of various slags are instructive in showing the wasteful results of early iron working processes, and in some cases the exceedingly high loss of iron to the slag. The Warrington analyses are also interesting as an indication of the widely varying properties which may be found in slags even when found at the same site. May's view that the lime present in the Warrington slags was an accidental impurity should be considered in the light of the low figures (2 to 8 per cent.), quoted by Straker. Lime is usually accepted as an intentional flux in the earlier processes, but this is a matter which could be investigated further with advantage. The wasteful results of the early processes, involving heavy loss of iron to the slag, were again noted by May at the Golf Links site at Tiddington, Stratford-upon-Avon (Fieldhouse, May, Wellstood, 1931, pp. 11-12). Here 53 per cent. of iron oxide remained in one sample of furnace slag while a piece of fettle, or fused lining from a smelting furnace, showed 44·4 per cent. of contained iron. Further results may be found in an interesting table of analyses of prehistoric iron slags given by J. W. Gilles (1936, p. 258), in his work on the prehistoric iron smelting in Siegerland, Germany. Some figures for Etruscan iron slag will be found in Witter (1942a).

THE DISCOVERY OF IRON

As we shall see later on, the discovery of how to obtain iron by means of smelting the ores was made at a very early date. It has not yet been established how, where, and when this discovery was made. It is not an entirely simple matter to explain how the discovery of smelting may have been made, and the complete answer to the problem of the discovery is highly unlikely to become known. An old theory to account for the accidental discovery of smelting is that of the camp-fire, but this is clearly an over-simplification. It has often been asserted that iron is not a difficult metal to smelt, and that if a suitable piece of iron ore, such as haematite, was accidentally placed in a large and hot camp-fire, reduction would take place, so leading to the discovery of iron smelting. From technical considerations it seemed to the author unlikely that the camp-fire was the birth-place of iron smelting, and to test the matter a number of experiments were carried out (Coghlan, 1941, pp. 76-77). A number of charcoal fires were made to simulate camp-fires and various pieces of iron ore, haematite, limonite, &c., were embedded in the heart of the fire so as to give the experiments every chance of success. However, no matter how large and hot the fire was made, it was found impossible to obtain a true reduction of the ore. In most of the experiments it was found that the ore had merely been roasted; once or twice, when an almost complete smother-furnace had been made, it was found that the ore had been converted into a cinder-like form which powdered to dust when lightly hammered. Nothing in any way resembling a sponge iron was obtained, nor indeed anything which could have been recognized by prehistoric man as appertaining in any way to iron or other metal.

Again, the difficulty of accidental smelting in an open fire has been pointed out by Dr. Rickard (1939, p. 86), who said, 'The iron ochres, which are the minerals limonite, goethite, and haematite, could be a source of metal if smelted in a hot charcoal fire within a closed vessel, but, as has been suggested previously, the accidental product from such a reduction in the open air would be so strange as to be unrecognizable as metal to the early metallurgist, and so imperfect as to be of no use to the primitive artificer.' Quite apart from the question of the discovery, accidental or otherwise, iron is not an easy metal to smelt without an adequate knowledge of how to do it. In this connexion Richardson's opinion as a technician must carry weight (1934, p. 575). He said that

it is not so simple as many modern writers seem to believe, to reduce iron in a shallow hole either with or without an artificial blast. A series of ten unsuccessful attempts had convinced Richardson of this fact. In only two of the ten experiments was there evidence of reduction and the process appeared incomplete in the one, while the other was over-carburized. Lack of success does not mean that it cannot be done. But would that conviction be equally strong where there had been no prior experience? To summarize, we may say that there are three important factors in the production of a useful metal by the direct process:

- (i) The ore to be smelted must be sufficiently protected by the fuel-bed against rapid oxidization which would be caused by contact with an excess of air.
- (ii) Some form of smelting furnace is required. The furnace may be with, or without, forced or induced draught.
- (iii) The furnace temperature must be high enough to enable the metal to reach a semi-fused or plastic condition so that a workable bloom be obtained.

It appears possible that certain pottery furnaces may have played a part in the discovery of smelted iron. First, it is clear that at a period well before the knowledge of how to smelt iron was discovered, there were developed pottery furnaces which could have attained the temperature necessary in order to reduce an iron ore. For example, some of the Tell Halaf pottery was fired at high temperature, from $1,000^{\circ}$ to $1,200^{\circ}$ C. (Speiser, 1927-8, p. 50). Concerning actual furnaces, large and elaborate pottery kilns have been discovered at Uruk, and at Susa in the second period. Again, in the levels of developed Tell Halaf and Samarra pottery at Arpachiyah, pottery kilns with domed roof and central pillar were discovered by Mallowan (1935, Pl. XXXI*d*). In such furnaces we know that the desired temperature could have been reached, and that the atmospheric conditions in the furnace could have been made reducing or oxidizing at will. Red ochre, or red oxide of iron, is a conspicuous and exceedingly widely distributed mineral, and we know that it was used by prehistoric man from Upper Palaeolithic times onwards; we also know that the red oxide was very widely used for the decoration of pottery from early times in western Asia. The point is worth consideration that, should some red ochre have been in one of these high-temperature kilns, and the atmospheric conditions in the kiln were favourable (that is, favourable to the reduction of the red ochre, but probably not the conditions desired for the production of fine high-baked pottery), a reduction

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of the ochre to metallic iron may have taken place. An interesting association of the pottery type of kiln with iron smelting in very much later times is worthy of mention. Miners quarrying iron ore for the Frodingham Company in Lincolnshire close to the hamlet of Woolsthorpe, in the parish of Colsterworth, found a remarkably perfect furnace or bloomery of the Roman period (Hannah, 1932, pp. 262-8). The natural soil (Upper Lias) is the ironstone which was being quarried. The furnace has marked affinities with a Roman pottery kiln, but it is to be noted that tuyère holes were provided, apparently for the purpose of blast. When found, the furnace was nearly empty. At the south-eastern end were abundant pieces of charcoal, much wood-ash, and partly reduced fragments of ironstone with apparent slag runnings on their surfaces. The ironstone was of excellent quality. One small piece of almost pure iron came to light, and more iron was found near to the furnace. An examination by A. E. Musgrave of a specimen of iron found embedded in the accumulation of wood ash and charcoal near the withdrawal end of the furnace showed that the specimen exhibited slag inclusions, and examination under the microscope gave support to the view that the iron was produced through the direct reduction process. A half-size model of the furnace is preserved in the Grantham museum. This discovery lends support to the theory that iron smelting may have an association with the pottery kiln.

On the other hand, it is perhaps rather labouring the question to associate the pottery kiln too closely with the question of the discovery of iron smelting. The following points are relevant to the problem:

- (i) That the discovery of iron smelting was preceded by a long tradition of copper smelting, and that by the time iron was discovered, prehistoric metallurgists had become highly skilled in, and had a very adequate knowledge of, copper smelting.
- (ii) That the knowledge of how to construct and operate large, high temperature furnaces had long been in existence.
- (iii) That it is not altogether unusual to find a deposit of rich iron oxide in the weathered outcrop of a copper lode (Rickard, 1932, ii, p. 837).

As an experienced engineer in the metal industry, Dr. Witter's opinion upon technical problems must be given due consideration (1942*b*, pp. 69-73). He considered that there is no doubt that the first intentional production of iron from ores was extremely difficult and laborious. Such a difficult operation as the first development of the iron technique could only have been undertaken by people who were familiar with the produc-

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tion and working of copper and bronze. Where iron first appeared, there must without doubt have existed a well-developed metallurgy. At a very early period it may have occurred that, here and there, copper smelters accidentally won iron in small quantity but did not know how to make use of the soft iron. Perhaps the copper-smelters accidentally, or for curiosity, collected haematite (which may outcrop in a copper-mining region), and which somewhat resembles in colour and weight the copper ore cuprite, and smelted the haematite. This would give them, instead of the soft red copper, a poor-looking black product that the copper-smiths would have tested to see if it was of any use. However, the iron with its slag and charcoal inclusions could only be forged and consolidated with great difficulty so as to yield a very little workable iron which could not be cast or hardened. It was therefore regarded as a costly metal without practical application in everyday life. Again, Witter says that copper pyrites is often associated with spathic iron ore. Here, there is a possibility of accidental iron production as a *Bär* or *ofen-sau*. Such production would belong to a later period for it depends upon a preliminary roasting process, and a high-temperature shaft furnace as well.

Taking the evidence at present available, the author inclines to the view that the discovery of iron smelting was most likely due to the accidental smelting of some iron ore, such as a haematite, found in the weathered outcrop of a lode which was being worked for copper. Should this have happened a number of times, there is no doubt that competent smelters would realize that they had found a new kind of ore which gave a very different metal from the copper to which they were accustomed. The question of why the iron industry took so long to develop after the initial discovery is an interesting matter which will be mentioned later.

ORES OF SUITABLE NATURE

Before leaving the subject of smelting a few words may be said concerning which ores are suited to working by the primitive process, for although iron ore is to be found in almost every country, for the discovery of iron and the development of an iron industry it follows that the ore must be of a nature well adapted to a rudimentary technique. In other words, it is more the kind of ore than the quantity or quality which is the important factor. In certain regions an obvious lack of technical ability renders it unlikely that such places would have been responsible for the discovery and growth of an iron industry. Again,

given suitable iron ore, one would expect the discovery of iron to have been made in a locality where a sophisticated copper culture was already in being. Small and scattered objects such as rings, beads, &c., cannot be considered as evidence for a true iron industry or, to use a modern term, true production. The first indication of a real industry would be the appearance of iron tools, weapons, and implements in some quantity.

Iron ores vary considerably in their richness and suitability. For example, magnetite when pure has an iron content of around 72 per cent., haematite an iron content of some 70 per cent., and spathic ore (siderite), a content of 48 per cent. Many ironstones are very much lower in iron than these; for instance, the Frodingham stone of north Lincolnshire is decidedly low in grade, the iron content when pure being only 22.7 per cent. This ore has, however, the important advantage of being self-fluxing owing to the large proportion of lime present in the earthy matrix of the ore. The Sussex ore may be cited as an ironstone which occurs in nodules and thin seams in a clay formation. Here again the matrix contains the lime which is needed as a flux. In his paper which we have already quoted Richardson makes some interesting observations regarding the suitability of various ores for primitive smelting. Of the spathic ores his opinion is that, once it had been discovered that spathic ores were reducible, it would follow that the process would be applied to the more difficult haematites and limonites which are so widely distributed, but the resulting iron would lack the consistent quality of that made from spathic ore. Again, an important point in favour of the spathic ores is that the acids and bases are more nearly balanced in the spathics than in other ores, and this is of considerable help in smelting under the direct reduction process. We must notice, however, that the spathics require a roasting operation prior to the actual smelting. Some writers have considered that early iron workers may have smelted ferruginous river sands, but such a source appears an unlikely one for early primitive workers. Richardson (1934, p. 566) has carried out experiments in this matter, the result of which are best given in his own words:

A series of preliminary experiments made by the author with black river sands, collected from various arroyas in southern Arizona, show that repeated washings are necessary to remove objectionable amounts of silica and gangue. This carefully done, a fine crystalline ore may be obtained with free iron running between sixty and eighty per cent. The ore particles after washing are so fine, however, that smelting in an open-fired furnace could never be carried out, no matter how carefully the drafts were controlled; hence the deduction that if the Chalybes smelted river sand, as Aristotle asserts, they must have evolved some

form of crucible process. But smelting carefully done in sealed crucibles with the addition of coal, or other carbonaceous material, would yield steel of varying hardness at will of the operator. It is suggested that possibly herein lies a solution of the traditional mystery of the excellence of Chalybean iron.

Przeworski (1939, p. 155) considers that in the prehistoric and early historic iron industry of Anatolia the only ores which would have been used were limonite and haematite, which were to be found in the upper surface. Magnetic iron ore he does not consider to be a suitable material for the early processes. Before 2000 B.C. there would not have been any intentional working of the haematite and limonite deposits and the isolated finds of iron objects point to an occasional gathering of ore. In Przeworski's view the preparation of the ore was as follows. In the primitive process the ore is first aired and the soluble compounds washed away, then follows roasting and crushing of the ore. Roasting (carried out in piles of burning wood), has for its purpose the removal of sulphur. Through archaeological finds we know that it was employed at Svanien, High Caucasus, around 1000-1100 B.C. Alluvial ore, that is, ore collected through natural causes in river beds, &c., needs only a simple washing process prior to smelting. However, Przeworski thinks that roasting and washing were commonly carried out in the Anatolian metal industry at least by the middle of the second millennium B.C. although direct archaeological evidence is lacking. As we have just mentioned, Przeworski postulates a roasting process as early as 1000-1100 B.C. in the High Caucasus, while Forbes (1950, p. 384) considers that washing and roasting of certain iron ores was an ancient practice in the Near East. However, he does not suggest any lower dating for the technique.

When we advance to Roman times there is no doubt that the practice of ore-roasting had become quite common. At Warrington (Wilderspool and Stockton Heath), Mr. May discovered smelting, roasting, and refining furnaces (1904, p. 23). At Stockton Heath clayband or impure ore was used as well as haematite. According to May the Romans as skilled metallurgists were most likely aware of the advantage of mixing these ores in order to obtain a more fusible charge and a better yield of iron, one ore supplying what the other lacked in the form of a flux to run off the combined silica and to set free the iron. Strangely enough the Roman founders at Warrington do not seem to have been acquainted with the use of lime as a flux.

Where it was available bog-iron ore was suitable for smelting with the direct reduction process. Weiershausen (1939, p. 92) points out that,

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because of its porous structure, permitting easy access by the reducing gases of the furnace, this ore was easy to reduce and therefore well suited to the technique of the prehistoric smelter. Clark (1952, p. 202) considers that iron ore was widespread in the northern territories of the temperate zone where climatic conditions, particularly during the Subatlantic phase, favoured the formation of bog ore. He makes the interesting observation that

Since the working of bog-iron survived down to modern times as a peasant industry in the northern countries, it has attracted a good deal of attention from Scandinavian researchers, and in Denmark at least has been shown to date back to the beginning of the local Iron Age. It is virtually certain that bog-ore similarly provided the main, if not the only, source of iron during early times in northern Britain.

We are unlikely to be able to determine which of the iron ores was first smelted by prehistoric man. It is of interest to note that Forbes (1950, p. 403), following Quiring, allows the possibility that magnetite was the first ore to be worked. Not, however, as a bloomery process, but as a crucible process and a by-product of the refining of gold.

The Nile sand, and especially the gold gravels of Nubia, contains grains of magnetite of high specific gravity and an iron content of over 65 per cent. About half the residue of gold washing is magnetite, the grains gathering with the gold dust and nuggets in the residue of the pan. Now the gold was smelted in Egypt in crucibles in a reducing atmosphere using chaff of clover and straw, as the texts tell us. After the smelting a slag rich in iron would collect on the top of the mass in the crucible, a layer of pasty iron would form the middle course directly over the liquid gold. If this pasty iron was extracted, it would be immediately ready for forging. It is clear that the quantities of iron produced in this way were small only. This method of iron manufacture as a by-product of gold would not only account for the peculiar association of small pieces of iron with gold in early jewelry, but it would also explain the pygmy character of the early iron objects, such as the small models (?) of tools, amulets, etc., found in the grave of Tutankhamen.

While this is an interesting theory it would need verification through experiment (simulating ancient conditions) before it could be generally accepted. Again, in Forbes's view:

As early as the first half of the 3rd millennium B.C., pieces of man-made iron appear in Mesopotamia (Tell Asmar, Tell Chagar Bazar, Mari), and Asia Minor (Alaca Hüyük), and possibly Egypt too. It is still uncertain what ores were worked first. Such brilliant 'metallic' ores like magnetite, haematite, iron pyrites and some striking forms of limonite may have attracted the attention of primitive smelters first. The use of haematite for seal-stones was widespread in Sumerian

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times and fragments of specular ore, a hard metallic variety of haematite, were found on the smelting site near the ziggurat of Ur (*Antiquaries Journal*, v, 1925, p. 391). On the other hand the ochres were used as pigments in pre-historic times, they are found in a soft form, rich in iron, and well adapted for rudimentary smelting operations.

From a consideration of these various views, and remembering that the problem may well have been a local one and not susceptible to any one solution, it appears likely that the first iron to be smelted came from an oxide (possibly of the ochre form). As experience was gained, carbonate ore would have been utilized, and finally sulphide ore in the form of iron pyrites will have been tested. It is almost certain that prehistoric miners would have noticed iron pyrites since it is very similar to copper pyrites both in colour and form, but it seems impossible that they ever successfully used an ore so difficult to smelt, and from which to obtain a sound iron. Somewhat similar difficulties were encountered, and finally overcome, in the case of the sulphide ores of copper, but for iron pyrites I do not know of evidence to suggest its use in early times.

MECHANICAL PROPERTIES

Although in antiquity the ferrous metal with which we deal was usually that known as wrought iron, to a limited extent we must take cast iron and steel into account. While remembering that steel is a modified iron, it is very necessary to avoid any confusion between the three metals, and to this end we cannot do better than to quote the definitions given by Straker (1931, p. 1), though his figures require some adjustment to conform with modern practice. Professor Forbes (1954, p. 595) quotes 1.5 to 5 per cent. of carbon for cast iron, and for steel a variation of between 0.15 and 1.5 per cent. of carbon.

Wrought Iron. Slag-bearing or weld-metal series. Containing very little carbon, say less than 0.3 per cent. This does not harden greatly when cooled suddenly. Highly malleable.

Steel. Intermediate between wrought and cast iron, containing between 0.3 and 2.2 per cent. of carbon, malleable, and capable of hardening by cooling.

Cast Iron. Not as malleable, containing 2.2 to 5 per cent. of carbon.

From the above definition it will be noted that the very great difference in the physical properties of the three metals is in the major part due to the changing value of the carbon content. Further, concerning cast iron, it may be accepted for practical purposes that the metal is not malleable. Malleable cast iron can indeed be produced, but only by means of a

modern technique which was certainly unknown in antiquity. Early wrought iron was a direct product of the primitive smelting furnace, and was a metal which had never been melted; today, practically all wrought iron is made from cast, or pig-iron, which has been poured in a liquid state from a high-temperature blast furnace of anything up to 100, or even more, feet in height. This pig-iron is converted into wrought iron by what is known as a 'puddling' process in which the pig-iron is again melted under certain special conditions in a coal-fired reverberatory furnace. From the reverberatory furnace the iron is removed in the form of a pasty mass containing much slag. It is then well hammered and again heated to a welding temperature and rolled into the required bars or sections.

Most of our modern steel is now made by so treating blast furnace pig-iron as to remove impurities. Two highly important processes are the Bessemer and the Siemens Martin open-hearth method. A good and brief description of the two processes has been given by Alexander and Street (1946, pp. 96-102). Here, we can only say that, in essence, the Bessemer process functions through burning away the impurities in the pig-iron by means of a special furnace known as a 'Bessemer converter', which blows air through the molten iron through blow-holes, or tuyères, furnished in the base of the converter. The open-hearth furnace is so called because the molten metal lies in a comparatively shallow pool on the furnace bottom or hearth. The steel is made by treating molten pig-iron and scrap steel with various additions. Also, a system of heat regeneration is used for the furnace which enables a sufficiently high temperature to be attained to treat a large quantity of metal, and to cast it into ingots when the metal has been made.

Concerning cast iron, when a modern blast furnace is charged with the correct mixture of ore, coke, and limestone (to act as a flux), and blown with a powerful air-blast, the product is of course cast, or pig-iron. Before it is ready to be used for making machinery, &c., the pig-iron from the blast furnace is subjected to further refining processes; according to the pig-iron selected various sorts of cast iron are obtained. In general, they may be classed into two main groups—the white and grey cast irons. These irons are defined by Alexander and Street as follows:

Both contain 2.5 to 4.0 per cent. of carbon, but the difference lies in the condition in which the major portion of the carbon exists in the structure of the metal. In the white cast iron all the carbon is present as cementite, and the fracture of such an iron is white. In grey cast iron most of the carbon is present as flakes of

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graphite, and there is usually a remainder which is in the form of pearlite; the fracture of this type is grey.

The archaeologist need only remember that white cast iron is intensely hard and very brittle. In modern practice malleable castings are made from white cast iron by means of a special annealing process, but in early times such treatment was, of course, quite unknown. On the other hand, the grey iron is not nearly so hard and is also much less brittle.

The ultimate tensile strength of cast iron varies greatly. For instance, the following figures for the ultimate tensile strength in pounds per square inch are given by Roberts Austen (1923, p. 26).

Cast iron. Weak 13,400. Average 16,500. Strong 27,300.

Under compressive stress the cast irons are very much stronger, but, on the other hand, they are very brittle when compared with wrought iron and steel. For wrought iron and steel we find very different conditions and for comparative purposes it is of interest to take the same series of figures for tensile strength quoted by Roberts Austen. These are:

Iron, wrought plates . . .	49,000 lb. per square inch.
Iron, wrought bars . . .	55,000 „ „
Steel, mild . . .	50,000 „ „
„ medium . . .	88,000 „ „
„ high carbon . . .	132,000 „ „

GILLES. TAFEL 7

Vergleich der Festigkeitseigenschaften von vorgeschichtlichen und neuzeitlichem Eisen

(Abmessung der Zerreißprobe: 5 mm. Dmr., 50 mm. Länge: der Kerbschlagprobe: 5 × 5 × 60 mm., Spitzkerb; 45°, 1 mm. tief.)

<i>Werkstoff</i>	<i>Eisenschund</i> 5/31	<i>S.-M.-Stahl</i>	<i>Thomas-stahl</i>
Analyse: C %	0.01	0.11	0.07
Si %	0.00	0.01	0.01
Mn %	Spur	0.41	0.49
P %	0.078	0.012	0.043
S %	0.011	0.028	0.03
Cu %	0.02	0.14	0.08
Streckgrenze Kg./mm. ²	21.6	21.1	28.0
Zugfestigkeit Kg./mm. ²	31.8	34.1	40.7
Dehnung %	23.0	36.0	31.0
Einschnürung %	66.0	75.0	73.0
Kerbzähigkeit bei + 20° mkg./cm. ² . . .	2 u. 7	2.8 u. 2.8	1.4 u. 1.2
Brinellhärte	88	103	118
Brinellhärte, abgeschreckt bei 680°, 14 Tage bei 20° gelagert	126	170	180

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Recently, enormous strides have been made in the development of high-quality alloy steels, so that we now have steels which possess tensile strengths of anything up to 100 tons per square inch. As not many investigations have been made upon the strength and properties of prehistoric iron, it is of interest to give the table by Gilles (1936) on p. 54, affording a comparison between a piece of prehistoric iron from the Siegerland, Germany, and two modern mild steels.

HARDENING, TEMPERING, AND CONVERSION TO STEEL

Before discussing the various methods of hardening iron we may here state the usually accepted meaning of the terms hardening, annealing, and tempering, as applied to steel. To anneal a steel of normal quality the metal is heated to a fairly high temperature, perhaps as high as a red heat, and then allowed to cool slowly. Unlike copper, steel cannot be annealed by heating and quenching; it is essential that the cooling be carried out slowly. Hardening, on the other hand, is the result of sudden cooling or quenching the highly heated steel. This treatment of high-carbon steel will render the material practically glass-hard and exceedingly brittle. The tempering of hardened steel is necessary to alter the structure of the metal so that it may be reduced in hardness while still retaining adequate strength and appropriate hardness for implemental use; to this end, the hard steel is again heated, but to a much lower temperature than was used in the hardening operation, after which it is allowed to cool. In this case, quenching in water or oil is usually resorted to.

Prehistoric iron was always made by the simple direct reduction process, and the product of the smelting furnace, that is to say a sponge iron, would have contained but little carbon, less than 0.2 per cent. It is well known that such iron cannot be hardened by heating and quenching in the manner that steel may be hardened. The carbon content of a modern steel which may be hardened usually ranges from 0.35 to 1.50 per cent., and it is this extra carbon content which imparts the property of hardening to the metal when it is heated and quenched; the extra carbon content is also one essential difference between prehistoric wrought iron and modern steel. Naturally one of the most important properties required in a tool or weapon is hardness, and although a certain measure of surface hardness may be imparted by hammering (that is, by work hardening), iron would only have become a really useful material from which to manufacture implements after the smith had discovered carburizing.

Adding a little extra carbon, or carburizing, may be achieved by high-temperature heating of the iron in contact with carbon as in the cementation process. The method used was to pack the iron in charcoal and to heat strongly for several days. This is a considered method, and while it is unquestionably an ancient one, from our point of view it may be a relatively late discovery. A similar result may be brought about (although naturally with much less exact control of the operation) by frequent heating and reheating of the iron in a charcoal fire. This must have been the method most anciently used, probably as an outcome of the hammering and reheating necessary to free the lumps of iron, as at first produced, from adherent slag and other impurities, also, to consolidate the metal which, as it came from the smelting furnace, would have been porous and full of blow-holes.

Even in pre-Roman times we have evidence to show that iron was subjected to some process whereby it was hardened. Two points are quite clear:

- (i) Soft wrought iron as produced in a primitive bloomery furnace is too low in carbon to be hardened to any marked degree.
- (ii) Steel, owing to its greater carbon content, may be hardened by heating to redness and suddenly cooling, as, for example, by quenching in water. As Rollason (1939, p. 94) points out: 'The essential difference between ordinary steel and pure iron is the amount of carbon in the former, which reduces its ductility, but increases the strength and the susceptibility to hardening by rapid cooling from elevated temperatures.'

Therefore to harden iron it must, at least in part, be converted to steel. Again, we must observe that, if a piece of steel is treated as mentioned under (ii), the material becomes hard and very brittle. In this condition it would be almost useless for implemental use and the further process known as tempering has to be resorted to in order to obtain a hard but serviceable metal.

In the tempering operation the hard steel is heated to a relatively low temperature and then quenched; the degree of hardness which the steel retains is relative to the temperature at which it is quenched. For instance, the lower the temperature at which the tempering is carried out, the less will the hardness of the steel be reduced. With modern thermostatically controlled furnaces there is, of course, no difficulty in the exact control of the process, but the ordinary working blacksmith tempers

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steel tools in a much more ancient and simple manner known as the 'tint' method. If a portion of the surface of a piece of steel is polished and the steel then heated over a smokeless fire it will be observed that successive changes in the colour of the steel will take place; for example, the bright steel changes to a straw colour, then brown, blue, &c. Jones (1921-2, iii, p. 874) states that each of these colours represents a definite temper or state of hardness of the metal between the two extremes of soft and glass hard. Hence it follows that, if the metal is quenched at any one of the various colours it will retain the temper appropriate to that colour. As Jones points out, the tint method is far from satisfactory by modern standards because the colours depend upon the duration of the heating as well as upon the actual temperature attained. On the other hand, the tint method is very widely used and very good results can be obtained by an experienced workman in the tempering of his hand tools; he tempers his screwdrivers at a straw colour, chisels and drills at a purple shade, and so on. It is not possible to know the technique adopted by the Roman or pre-Roman smith for his tempering; probably he had no very clear idea of what he was doing. He must, however, have been guided by some observed results and it seems not impossible that he may have noticed the changing colours in a piece of carburized iron, which for some reason had been polished, and had associated the colour changes with temperature changes. As with the discovery of smelting, we can never know the exact circumstances which led to the important practical result. Finally, it is of interest to quote Richardson's remarks concerning the difficulty of the tempering operation.

It is impossible as yet to affirm or deny that the Romans tempered their carburised iron. The broad assumption is that they did, for it is quite inconceivable that having advanced to this final, all-important phase of heat treatment they could fail to complete the cycle. On the other hand, successful tempering requires controlled temperatures regulated to the varying composition of the iron carbide alloy. Tempering would, therefore, be only possible in those favoured localities where repetitive operations with a uniform product afforded opportunity for observing the effects as measured by the various oxidation colours. Even at best the difficulties were enormous and the results always uncertain.

As we have already pointed out, in order to convert wrought iron into a steel which may be hardened, the essential thing is to increase the carbon content of the iron. In the earliest times this result was no doubt accidentally obtained by carburization which was due to repeated forging of the iron while heated in close contact with the charcoal of the smith's

hearth. As a special case, it may be noted that Forbes (1950, p. 409), while doubting the possibility of the direct production of steel by the ancients, considers that steel was accidentally produced under suitable conditions of ore and furnace. In his view there was a possibility of producing steel from a bloomery furnace when smelting manganese-bearing ores which were free from phosphorus, arsenic, or sulphur. If the bloom was not decarburized fully, a good malleable steel would be obtained. Some such conditions may account for the quality of the Celtic iron from Noricum, and Forbes thinks that the shaft furnaces of the region would have been well suited to the accidental production of such 'natural steel'. Such occasional production of natural steel need not be confined to the spathic ores of Noricum. It may have existed at other metallurgical centres, and may well be the reason for the renown of certain ancient iron cultures.

Again, Weiershausen (1939, pp. 192-3) considers that to make low-carbon steel in the early smelting furnace required no change in the furnace construction, but called for a different method of operating the furnace, and for the use of a suitable ore. In his opinion, 'brauneisenstein' is the most favourable ore to use and the following procedure was observed. The furnace was thoroughly preheated so that the highest temperature could be attained; also much more charcoal but less ore than usual was charged. The oxidizing effect of the air draught was reduced by suitable inclination of the air passages in the case of natural draught, or with forced draught the tuyères were set a little higher than usual. The bloom had the shape of the furnace-well on its underside, and the iron thus lay at a low level and so was less influenced by the oxygen in the air-stream. Long immersion in a slag bath has a decarburizing effect, but with a manganese-bearing slag the carbon content will remain constant for several hours. Hence, the use of brown iron ore is helpful in the above process.

The cementation process was certainly an ancient one. Here, the conversion of strongly heated but still solid iron into steel is effected by the passage of solid carbon into the interior of the mass of iron (Austen, 1923, p. 56). This change in the properties of the iron was usually brought about by a controlled heating of the iron, at elevated temperature, within closed receptacles containing carbonaceous matter, over a more or less prolonged period of time according to the nature of the steel which it was desired to make. Until quite recently (possibly even at the present time), a small quantity of commercial steel of special

quality was made by the cementation process. Lucas (1948, p. 275) points out that iron only became a thoroughly serviceable material for implemental use after the discovery of carburizing, and in his opinion carburizing may be brought about by allowing the iron to remain in contact with carbon at a high temperature when some small proportion of the carbon will be absorbed by the iron. The amount and depth of penetration naturally depend upon the length of time during which the hot iron and carbon are retained in contact. Experiment has proved that the absorption of carbon is greatest at the surface and gradually decreases towards the centre of the mass. For many centuries the method would have been purely empirical, and the smith can have had no understanding of the principle involved.

References to steel in pre-Roman or Roman times should be examined with care. Such material is generally that which has been modified by carburization until it exhibits some of the characteristics of what we now call steel. Again, it may be a steel by cementation. Sometimes the hardening is but a thin 'case'.¹ Carpenter and Robertson (1930, p. 417) have carried out valuable research treating of the metallography of some ancient Egyptian implements. From this work it would appear that, by means of carburizing and heat treatment, the ancient smith was able to impart useful properties to the tools made from primitive iron. Further, it seems that even the earliest iron examined had been carburized, iron of an intermediate period had been carburized and quenched, while the latest (of Roman period, A.D. 200) had been carburized, quenched, and finally tempered.

Some modern primitive iron workings afford a demonstration of how carburization must have been carried out in early times. In this connexion Rickard (1939, p. 98) points to primitive iron smelting as practised by the natives of Mashonaland, in Southern Rhodesia, an account of which has been given by Professor Stanley (1931). Here, the product of the smelting furnace is a lump of spongy iron of about 20 inches in diameter. The iron as recovered from the furnace is very cellular, containing marked inclusions of slag and charcoal, and when cool is broken into pieces of suitable size for forging. In Professor Stanley's own words:

The number of heatings and forgings the metal undergoes, and the patience displayed by the artificers, are alike extraordinary to one used to modern methods but, of course, it is easy to see how the slag in some cases is hardly all beaten out,

¹ The new metallurgical research recorded in Chapter X is a most welcome addition to our knowledge of 'ancient steel'.

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while the inclusion of actual pieces of charcoal in the sponge-iron, and its gradual absorption and diffusion during working, quite sufficiently explain the production of steely iron and the unhomogeneous structure.

The above account makes it clear that the iron undergoes some considerable measure of carburization during the repeated forging operations.

Also referring to African iron of primitive origin, Cline (1937, pp. 53 ff.) says:

When we polish a section of native iron, lightly etch it with acid, and examine it under a low-power microscope, or even with the naked eye, we see that it has a very non-uniform consistency. The slag entangled with it will appear almost everywhere as dark swirls, ripples, and blotches on the light background of the pure wrought iron. Often, however, the surface is marked with several intermediate shades. These represent iron carbide, and a sufficient proportion of this compound to make the material harden at sudden cooling will bring it within the category of steel. If we separate and chemically analyse these areas of differing darkness we find that their carbon content ranges all the way from zero in the pure iron to 0.9 per cent. in the iron carbide.

It may also be noted that steel may directly be made by smelting certain classes of ore, but this would hardly have had any wide relation with the prehistoric process.

On the subject of hardening iron, Richardson (1934, pp. 53 ff.) makes some interesting observations concerning the part played by forced draught in the process. In his view, if unit production was only slightly increased by the employment of bellows, a marked improvement in quality may be traced to their use. This would be especially true with the manganiferous spathics of Noricum, from which the iron-master of the Empire could make steel or high-carbon iron at will. If a hard iron were desired, more and thicker charcoal would be added, and by continuing the process longer with a reduced draught carbon was absorbed in approximately the required amounts. To obtain a soft iron the process would be reversed.

Chapter IV

THE EARLIEST SMELTED IRON AND CAST IRON IN ANTIQUITY

ARCHAEOLOGICAL NOTES UPON THE EARLIEST SMELTED IRON

WE may now consider the earliest finds of smelted iron in the Old World. Rare objects of iron have been found in the third millennium B.C., and in considerably greater quantity in the first half of the second millennium, while towards the end of the second millennium iron becomes well established in certain regions of the ancient Near East.

III Millennium Iron

At Tell Chagar Bazar in north Syria a fragment of iron was discovered in level V (Mallowan, 1936, p. 26), which the excavator considered to be not later than 2700 B.C. Professor Desch reported that the metal was completely oxidized, and contained 51·36 per cent. of ferric oxide, corresponding with 35·95 per cent. of metallic iron; the remainder would consist of foreign matter derived from the soil. The specimen contained no nickel and was therefore not of meteoric origin. Again, in 1937, Mallowan (1937, p. 98) said:

Two fragments of iron supply further proof that the Habur was a very early centre for the working of iron in the third millennium B.C. Both these specimens come from level III and cannot be later than 2500 B.C. It is, I think, almost certain that these two fragments, which have yet to be analysed, will prove to be of terrestrial origin, as was the fragment of a dagger blade discovered in level V in the course of the first campaign.

Another highly important find is the bronze hilt which held the remains of an iron blade found at Tell Asmar. Of this, Dr. Frankfort (1950, No. 160) says:

The temple service, a closed find, to which the knife belongs, was buried at the very end of the Early Dynastic period, say between 2450 and 2340 B.C. It is relevant that this blade of terrestrial iron was mounted in an openwork handle of bronze while the other objects of the hoard, some 75 pieces, were made of copper. The knife may therefore not have been of local manufacture.

The iron was analysed by Professor Desch (*RBA* 1933, p. 302) who reported the material to be rusted iron, converted as usual by long contact

with the earth into a hard magnetic, crystalline mass. The iron was free from nickel and was therefore not of meteoric origin.

A very fine dagger with gold-sheathed handle and iron blade is associated with the Royal Tombs at Alaca Hüyük in Anatolia (Koşay, 1951, p. 167, pl. lxxxii. 4). From the usually accepted dating for these tombs, the Alaca dagger no doubt belongs to the end of the third millennium B.C. Also, from period III of Alaca Hüyük came an iron pin with a gold-plated head, and a fragment of a crescent plaque. These are mentioned on p. 33, as the analysis suggests a meteoric origin for the metal. Recently, during the course of excavations at Geoy Tepe, in Persian Azarbaijan, Burton Brown came upon evidence for early iron working (Brown 1950, no. 4, 1951, p. 199). In the D period at Geoy Tepe (which the excavator places in the later part of the third millennium), a piece of iron was found. Analysis proved this to be of white cast iron. Such a remarkable piece can only be accounted for as the result of the serious overheating of a high-temperature furnace. The cast iron would, of course, have been useless, for it would have been impossible to work it at that time. However, further evidence for iron working was found in the D or C period, and again in the A period which can be dated to the beginning of the Iron Age.

II Millennium Iron

Mesopotamia. In Mesopotamia iron is first mentioned by the cuneiform tablets in the time of Hammurabi. From the Hurrian period there is a curious inversion in the use of metal in a dagger from Yorgan Tepe (Nuzi), where the blade of the weapon is of bronze, while the hilt is of iron (Starr, 1937, Tf. 125). Parrot (1938, p. 310) reports fragments of iron found at Mari near the remains of the pre-Sargonid temple of Ishtar. Forbes (1950, p. 446) states that iron weapons and tools appear in the Kapara period at Tell Halaf, together with a movable hearth, probably a brazier. The general use of iron tools and weapons in Mesopotamia was of late occurrence; probably not until 900 to 800 B.C. did their use become really general.

Persia. In Persia one would expect to find evidence for iron working during an early period. However, on the evidence so far available it would seem that the first Iranian iron production is relatively late. For instance, the iron objects of Tepe Giyan I and Tepe Sialk A are nearer to the end than to the middle of the second millennium, while the rich iron production of Luristan falls only within the first millennium B.C. In

Luristan, while bronze still prevails, many objects dating from around 1000 to 750 B.C. are composite, the working parts being of iron while the non-functional parts remain of bronze.

Syria and Palestine. In the first half of the second millennium iron remains very rare. After about 1500 B.C. there is quite a marked increase, and from around 1300 to 1200 B.C. we find evidence for the beginning of a true iron industry. During the first part of the second millennium iron was, of course, so rare that the iron objects are limited to those of a ceremonial or ornamental character. One of the most notable, although later, pieces is the very fine battle-axe discovered at Ras Shamra on the Syrian coast by Schaeffer (1939, pp. 110 ff.; Lamb 1940, p. 393). This axe was deposited *ex voto* in a little sanctuary apparently forming part of an important building dating from the end of the fifteenth century B.C., or to the first half of the fourteenth century. The axe was made from three different metals, copper and gold for the socket, and iron for the blade. The material of the blade would more accurately be described as a nickel steel (see p. 34), for analysis gave the following composition:

Iron 84.95 per cent. Nickel 2.25 per cent. Sulphur 0.192. Phosphorus 0.39. Carbon 0.410. Oxide of iron 10.8 per cent.

Also from Syria Przeworski (1939, p. 141) mentions the following finds. A gold-plated iron amulet of the time of Amenemhet III was found in a Royal tomb at Byblos (Vierleaud, 1922, pp. 286 ff.; Fig. 6). Later there is mentioned in the temple inventory of Katna at the time of Thutmosis III seven iron objects of which six were gold-plated (Vierleaud, 1928, p. 92; 1930, pp. 334, 337, 339). In a late Bronze Age level at Gezer in Palestine was an iron ring, and two iron axe-blades which were found in a water tunnel, and may be ascribed to the same period (Macalister, 1912: i, p. 301; iii, pl. 63, p. 61; ii, pp. 269 ff., Fig. 417). From Tell el Mutesellim III (Megiddo) comes a tool with an iron handle (Schumacher, 1929, Fig. 98).

Finally, from Minet el Beida came beads and iron rings which were evidently regarded as of great value, since they were buried with gold and silver (Schaeffer, 1929, p. 292). At Lachish (Tell el Duweir), there is no record of very early iron. The iron excavated (Tufnell, 1953) dates back to about 1100 B.C., but the majority of the iron so far excavated is of considerably later date. According to Wright (1939, p. 459), in Palestine iron was introduced for a variety of implements in the late twelfth and eleventh centuries B.C. The sites with datable iron objects

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from these periods are Tell el-Far'ah, Gerar, Beth-shemesh, Gezer, Tell el-Hesi, and Tell el-Ful.

Although the evidence is decidedly scanty, it appears possible that smelted iron was known in Palestine by the middle of the second millennium B.C., and even earlier in the north in Syria.

Anatolia and Trans-Caucasia. The occurrence of early iron at Troy is confused and doubtful. According to Forbes (1950, p. 450) useful iron may not appear before the destruction of Troy VI in the twelfth century B.C.

The oldest iron remains of Trans-Caucasia come from the late Bronze Age kurgan, number 28, of Helenendorf in the Gandža-Karabāg district. In Georgia and Armenia iron objects do not appear before 1200 B.C. and then they are rare (Przeworski, 1939, p. 139). It may be said that in general, iron is of late occurrence in trans-Caucasia.

Crete and Greece. We have mentioned some finds of early meteoric iron in Crete, and it would appear that smelted iron was also known, although but little used in the second millennium. Przeworski (1939, p. 143), following Mosso, mentions slag derived from the reduction of oxidized ores at the great Tholos of Hagia Triada. Objects of the finger-ring class appear to be known after 1500 B.C., but in general, iron in Crete only attained importance after about 1200 B.C. It is likely that iron in Crete was a foreign metal, for there are no notable deposits of iron ore in the island. A large and interesting class of prehistoric iron objects are the finger-rings (Childe, 1939, p. 28), mostly found in Mycenaean graves and usually built up of successive layers of different metals. They are in fact dry batteries, precursors of galvanic rings and so their magical value may rest on some basis of scientific fact. The Phaestos ring has a bronze core overlaid with gold for one-half of the circle and with iron for the other. A similar ring is in the National Museum at Athens. At Dendra, near Media in Greece, Professor Persson found four metal rings of which three are composed of four layers of metal in the following order from the exterior—iron, copper, lead, and silver. Excluding the iron ring found at Vorwolde, in Sulingen, Hanover, which merely consists of iron oxide, these composite rings are dated from *c.* 1500 to 1200 B.C. Iron comes into regular use for weapons, &c., in Greece with the Proto-geometric period, at least in the less backward parts of the country. Desborough (1952, pp. 308-12) may be referred to for lists of this later iron.

For Greece and Crete a useful summary of the evidence is given by

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H. L. Lorimer (1950, pp. 111-12), from whom the following list of iron objects of the Bronze Age found on Minoan or Mycenaean sites is quoted.

1. Small cube of iron from pit with MM II¹ contents in chamber-tomb in Mavro Spelio cemetery at Knossos; *BSA.* xxviii, pp. 279 and 296.
2. Ring from the Vaphio tholos tomb; period of transition from Shaft-grave culture to LH II; *Eph. Arch.* 1889, p. 147.
3. Front half and bezel of bronze ring partly overlaid with gold from tholos at Kakovatos contemporary with the Vaphio tholos; *AM.* xxxiv (1909), p. 275, pl. xiii, no. 35.
4. Iron nail from Knossos with an ornamental gold head; *BSA.* vi, p. 66. Not precisely datable; LM I or II.
5. Half of bezel of ring from an LM tomb at Phaistos; *Mon. Ant.* xiv, p. 593, fig. 55.
6. Three rings of iron, copper, lead, and silver from the King's Tomb at Dendra; Persson, *The Royal Tombs at Dendra*, p. 56; first half of fourteenth century.
7. Iron stud with gold head at either end from Chamber-tomb 2 at Dendra; Persson, *ibid.*, p. 79; thirteenth century.
8. Iron pendant overlaid with gold from same tomb; *ibid.*, pp. 102-3.
9. Fragments of an iron ring from Chamber-tomb I. i at Asine, end of LH II or LH III; Frödin and Persson, *Asine*, p. 373.
10. Two iron rings from Mycenaean chamber-tombs, presumably LH III; *Eph. Arch.* 1888, pp. 135 and 147.
11. Traces of iron on one of several lead clamps used for attaching door-jambs to walls of palace of Gha in Boeotia; LH III; Tsountas and Manatt, *The Mycenaean Age*, p. 381.

Egypt. Maspero's finds of iron from Saqqarah, Abusir, and Dahshur, as well as the piece of iron reported by Vyse as from the Great Pyramid, might be taken to indicate that the knowledge of iron smelting was early in Egypt. Actually, the evidence is not sufficiently satisfactory to enable us to place any reliance on their archaeological dating. The doubtful pieces of iron are:

- (i) The well-known piece of iron from the Great Pyramid of Giza, supposed to belong to the IVth dynasty.
- (ii) Various pieces of chisels from Saqqarah. Ascribed to the Vth dynasty.
- (iii) Several pieces of a pickaxe from Abusir. VIth dynasty.
- (iv) Some broken tools from Dahshur. VIth dynasty.
- (v) A lump of iron rust, perhaps a wedge, from Abydos. VIth dynasty.
- (vi) A large spearhead from Nubia. XIIth dynasty.

¹ MM. = Middle Minoan. LM. = Late Minoan. LH. = Late Helladic.

It is a distinctly suspicious list. The piece of iron from the Great Pyramid at Giza has been examined and found to be of smelted origin (Desch, 1928), but it appears doubtful whether the piece really is of the age which has been assigned to it; there is the possibility that the iron may have been a tool belonging to one of Vyse's own workmen which slipped down during the course of the excavations. The finds from Saqqarah, Abusir, and Dahshur are all reported by Maspero, and the evidence does not appear to be sufficiently satisfactory (to the modern archaeologist) to warrant these objects being considered authentic in regard to the dating proposed. Of the iron rust found by Petrie at Abydos, Lucas (1934, pp. 195-6) says that the rust was tested chemically and was not of meteoric origin, also that there is no proof that it was a tool or implement, and that it is a mystery how it came to be placed in the foundations of a temple at Abydos. There are various difficulties in the way of accepting the Nubian spearhead, although the finding and dating would appear to be in order, and the metal has been analysed and found to be of smelted origin. However, the type is modern (Wainwright 1936), and it seems unwise to accept this single specimen as evidence for iron smelting in the XIIth Egyptian dynasty. Of more importance is an iron deposit which was found on a flint wand by Reisner in the Mycerinus Valley Temple at Giza, IVth dynasty. The deposit in question (Dunham and Young, 1942) was spectrographically examined by W. J. Young, who stated that the material must have been iron in its ferric state. No evidence of nickel was observed, so that the iron was not of meteoric origin. The inference is that the 'magical set' found by Reisner included some piece of terrestrial iron. It appears probable that Egypt was one of the last of the ancient civilizations to enter the Iron Age. No doubt smelted iron gradually became known during the New Kingdom, possibly after 1400 B.C., but the metal cannot have been well established until many centuries later. Indeed, Lucas (1948, p. 273) considered that on the evidence so far available the earliest working of iron ores were the smelting operations at Naucratis in the sixth century B.C. discovered by Petrie, while Forbes (1954, pp. 596-7) thinks that the Iron Age proper does not begin before 600 B.C. It is not unnatural that the Egyptians should have been slow in adopting iron. First, because they had built up a very extensive industry in copper and bronze which no doubt seemed quite adequate to them for their needs. Secondly, while there are iron ores in Egypt, the ores may not have been easily worked, or of the quality required to suit the early technique. Again, iron could

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not have been cast like copper and bronze and it is a far more difficult material to forge than copper. This would be a matter of considerable importance to the Egyptians in view of their limitations in tool equipment, and in particular of their traditional dislike of using the shafted hammer.

India and China. Evidence for the first occurrence of iron in India is uncertain, but in general it would appear that the Iron Age in India is relatively late. Forbes (1950, p. 436) considers that there is proof that iron was known in the Rigvedic Age. In his view iron was introduced into northern India by 1000 B.C. or even earlier. In southern India, not until between 500 and 200 B.C. do iron tools and weapons become common. In a recent work Colonel D. H. Gordon (1950, p. 67) considers that there is no material evidence to prove that iron was introduced into India or Pakistan earlier than the beginning of the first millennium B.C., and it appears likely that the event occurred sometime between 700 and 600 B.C., although such a date is speculative and not backed by concrete evidence.

Forbes (1950, pp. 440-1) considers the antiquity of iron in China to have been exaggerated, and that it has lately been proved that the transition from bronze was in the Tsin dynasty, 255 to 209 B.C., and in the early Han dynasty of 209 B.C. to A.D. 25. In the later Han dynasty, China was in the full Iron Age. The Chinese have a good claim to be the first people to have made really practical use of cast iron. Complicated objects such as stoves were cast in iron during the later Han dynasty. This is a remarkable technical achievement both in founding and in moulding. The key to the process would appear to be that the iron was melted together with coal in crucibles. The high phosphorus content of the coal had the effect of much reducing the melting-point and rendering casting easy. Castings of remarkable size were made. Forbes mentions a Buddha of 5 metres in height from Tsinanfu dating from the sixth century, while a cast-iron lion of A.D. 953 is quoted as being no less than 20 feet in height and 18 feet in length.

Archaeological Notes

During the early appearance of iron the use of the metal was very limited. In the Near East the first iron seems to have been used (on account of its scarcity and cost) for amulets and ornamental purposes only. Later, when more iron became available, although it was still a rare metal, iron was often incorporated in part of a weapon. For instance, in

a dagger the blade might be of iron while the hilt was of bronze: next, when iron came into more or less general use we find the whole tool or weapon made of iron and the forms of the various objects become conditioned to the properties of the new metal.

The objects of third- and early-second-millennium iron so far recorded are far too scanty to permit of a distribution map which would be of any real value in determining the focus of the first iron working. We can only indicate its probable origin as somewhere to the north, or north-east, of the Fertile Crescent. It may be helpful to mention some views expressed by Schaeffer in his latest work (1948, pp. 297, 546). In his view, the opinion that the most ancient objects of manufactured iron are of Assyrian origin can no longer be maintained. His view is that, given what has been learned from the El Amarna texts concerning the origin of iron in the fifteenth century B.C. and now that many objects of iron of such high antiquity have come from Asia Minor, it no longer seems prudent to refuse the paternity for the origin of iron to the Anatolians, and perhaps more particularly to the inhabitants of the Armenian regions. Due to their experience it is probable that the metallurgists of Asia Minor became the first producers of iron in quantity when, after the thirteenth century B.C., this metal supplanted bronze for the manufacture of arms and weapons in the Ancient East. Again, Schaeffer thinks that, having lost the monopoly of mineral exploitation, and of the manufacture of bronze hardened by appropriate alloys, the metallurgists of Asia Minor and Armenia were nevertheless able to guard the secret of the manufacture of iron. From the end of the third millennium they had been able to master the difficulties of extracting this metal. To judge from the discoveries actually known, iron was not in use anywhere during the Middle Bronze period, even for royal armament or decoration.

The disappearance of the metal after its first utilization at the end of the Ancient Bronze period, and its apparently total eclipse during all the Middle Bronze period, is a very curious and interesting phenomenon. Iron only appears to have been rediscovered during the Recent Bronze period and, from all the evidence, in the same region, that is, Asia Minor. This gave the metallurgists of the region an increased reputation and a new period of prosperity when, during the final Bronze phase (corresponding to the New Hittite Empire), iron commenced to be adopted, first for armament and then towards the end of the period for tools, by all the civilizations of Western Asia. The disappearance of iron after its first utilization, if indeed future research confirms that it did, in fact,

actually disappear, may perhaps be ascribed to the difficulty of working the iron without an efficient equipment of tools. We must remember that, unlike copper, iron has to be forged hot; for such work smiths' tongs are very necessary, but early in the third millennium they were almost certainly not available. As we shall see later, a second important reason is that iron made by the primitive process is soft, and of little value for cutting tools because it is not possible to impart sufficient temper to the blade to obtain a good and durable cutting edge. So long as the early iron blades had only soft copper tools to compete with, they would have been of value for they were, of course, considerably harder than copper. When good bronze became available the position was a very different one. Figures for the relative hardness of soft wrought iron, and bronze of around 10 per cent. tin content, clearly show that a good bronze when fully work-hardened is considerably superior in hardness to the primitive iron. Hence, it would not be so surprising if it were established that the introduction of bronze checked the development of iron for some centuries until the iron workers had discovered how to produce iron which could be hardened, and had also evolved a suitable kit of tools to deal with the forging and other processes.

The chief basis of the often repeated story of a Hittite state monopoly of iron-working is the well-known letter found at Boghazköi, *Keilschrifttexte aus Boghazköi*, i (1916), p. 14. As some of the far-reaching reconstructions built on this text have been frequently repeated as if they were proven facts, it is important to remember how hypothetical they are. The circumstances in which the letter was written are entirely obscure and all inferences about motives are unfounded guesses. The writer is generally, and reasonably, thought to have been Hattusilis III, but the addressee is unknown. There is no evidence for the older view that he was the Egyptian Pharaoh (Rameses II), and recent opinion inclines rather to Shalmaneser I of Assyria (so Cavaignac in *Rev. hittite et asiatique*, ii (1934), pp. 233 f., and recently Goetze, *Kizzuwatna and the Problem of Hittite Geography* (1940), chap. III).

This letter and others among the Amarna letters show that iron weapons were rare, much prized and fit royal gifts. But as Goetze says (op. cit. 33), 'There is no reason whatever for the belief that the Hittites wished to monopolise the precious metal for themselves. Nothing indicates that sending the weapons would have involved military secrets. The contemporary Amarna letters are full of similar requests.' The Hittite king's failure to oblige his correspondent is capable of various

explanations compatible with the scanty evidence. That he was making excuses because he did not want to send iron is one such possible explanation, but there is no reason for doubting that there was a genuine shortage. It is possible that, as has been suggested, iron working may have been a seasonal occupation for the peasants at times when there was no other work (so Gurney, *The Hittites*, 83), or that there may have been religious or magical reasons preventing the work (Contenau, *Manuel*, iv, p. 1893). Nor does the Boghazköi letter imply that iron was *produced* at Kizzuwatna, but only that iron weapons were stored there. For the approximate location of Kizzuwatna there is now virtual agreement among scholars that it coincided, partly at least, with Cilicia. The arguments are given fully by Goetze (op. cit.).

While we cannot agree, it is only right to give Przeworski's opinion, although this dates back to 1939, as he made a valuable study of the Anatolian iron industry (1939, pp. 161 ff.). He considered that the formation of the iron industry in the east Mediterranean and Near Eastern region took place after many hundred years of development of iron working. Even in its first beginnings it was not confined to a definite find-spot, but was assignable to various lands at the same time; therefore a single source for the ancient oriental iron industry cannot be allowed. Its building up was the result of tedious general search and experiment of the whole Near Eastern world. Przeworski admits that these views contradict the frequently cited hypothesis that the Armenian-East Anatolian highland was the home of ancient oriental iron metallurgy; he considers that the early iron finds of the Near East in no way prove that Anatolia was in advance of other lands in any stage of development of iron metallurgy. The evolution of the early Anatolian iron industry was closely allied with that of the neighbouring regions, and in general ran a parallel course. If this view be accepted, the Asia Minor branch can have no pretensions to the discovery of iron technique, although it greatly assisted in its improvement and development.

Richardson (1934, pp. 556-7) considers that some regions made a rapid advance to a developed bronze culture, but seemed reluctant to take the next step and go forward with iron. Egypt offers a classic example, for no doubt Egyptian metallurgists had knowledge of iron, and some attempts may have been made to apply their knowledge, but at great cost a stable and profitable copper and bronze industry had been built up which met every present need, and so far as could be seen would continue to meet the Egyptian needs. The change over was delayed by

the fact that, while iron might be a metal of future promise, in the immediate present it was no better than bronze.

To conclude this very brief survey of the archaeological record, it may be said that there is a considerable amount of recorded iron as a result of excavation in various countries of the Old World but, particularly before the dispersion of the Hittite Empire in the twelfth century B.C., the evidence is scanty and inconclusive. The archaeological history of the development of the iron industry will remain dark until we have more material, and much more scientific examination, of past and future discoveries. Apart from the sporadic occurrences of iron objects in very early contexts which are known in the Ancient East, it may be said that the making of hard and useful iron was most likely achieved by the Hittites as early as the fifteenth century B.C.; while around 1200 B.C. there was an important general increase in the production of iron, and it may be said that a true iron industry dawned. For the transition of iron-working to Europe upon any extensive scale some considerable time was required. Clark (1952, pp. 199-200) mentions a first establishment of iron working in Greece and the Aegean around 900 B.C. From the eastern Mediterranean the knowledge was brought to Tuscany possibly by 800 B.C., but it was not until about the middle of the seventh century B.C. that iron working really became established in the Alpine regions, afterwards to be widely distributed in Central and western Europe under Hallstatt influence.

Cast Iron in Antiquity

The Material. As a material, cast iron is very different from wrought iron or steel. It is brittle and cannot be shaped by forging, but it has the advantage that it pours easily and can therefore be cast to any required shape in the same manner as the non-ferrous metals. Steel may of course also be cast, but that is a modern high-temperature process which could have no application in the times of which we treat. The basic difference between our primitive wrought iron and cast iron is that, when iron is liquefied in a blast, or other high temperature furnace, it absorbs from 3 to 5 per cent. of carbon and other impurities. It is this absorption of carbon which gives the iron hard and brittle properties when it solidifies. In modern practice the 'pig iron' from the blast furnace is not used without further refinement by which the original iron is controlled in composition and suited to the various manufacturing requirements. However, in general, there are two main classifications into 'grey cast iron'

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and 'white cast iron', both containing between 2.5 and 4 per cent. of carbon (Alexander and Street, 1946, pp. 114-15).

For our purpose it may often be necessary to distinguish between these two varieties of cast iron, and the essential difference is in the condition in which the major part of the carbon exists in the metallic structure. The terms white and grey refer to the appearance of the metal when it is newly fractured. In the white iron, all the carbon is present in the structure in the form of cementite, while in grey iron most of the carbon is to be found in graphitic flakes with a remainder in the form of pearlite. Since cementite is extremely hard, it follows that white cast iron is very hard but brittle, while the grey iron is rendered soft and less brittle by the graphite flakes. Also, it is important to note the relatively low melting temperature of the grey iron, 1,140° to 1,200° C.

The following groups of cast irons, and Fig. 3 (see p. 73), showing some structures of cast iron, are taken from E. C. Rollason (see 1939, fig. 104 and p. 190).

Free cementite + pearlite, *d, b*—white, hard, unmachinable.
Cementite + graphite + pearlite, *f*—mottled, difficult to machine.
Graphite + pearlite, *e*—grey, machinable, high strength.
Graphite + pearlite + ferrite, *c*—grey, soft, weaker.
Graphite + ferrite, *a*—grey, very soft, easily machined.

As we have noticed in the case of iron and steel, the term 'cast iron' may cover very considerable variation in the actual composition of the metal. Hilton (1953, p. 97) gives the following range of variation which exists between the various grades of cast irons as now produced:

Graphitic carbon	.	.	.	1.0 to 3.75 per cent.
Combined carbon	.	.	.	0.2 to 3.0 "
Silicon	.	.	.	0.2 to 3.5 "
Manganese	.	.	.	0.2 to 1.5 "
Phosphorus	.	.	.	0.02 to 1.5 "
Sulphur	.	.	.	0.01 to 0.1 "

All the primitive iron of the period with which we are dealing was wrought iron as distinct from our modern iron which is very frequently melted and cast. In the normal primitive smelting process, as the ore becomes reduced and falls down through the various zones of the fire, the oxidizing flux causes a partial decarburization, the melting-point becomes raised, and the temperature is only enough to enable the iron to collect in a sponge-like form at the bottom of the furnace. There could

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have been no question of melting the wrought iron after it had been produced by the founder, since the temperature required to melt wrought iron is approximately $1,530^{\circ}\text{C}$., considerably above the temperature range of any early furnace (Coghlan, 1941, p. 77). When furnace technique had advanced sufficiently and tall furnaces, blown with artificial

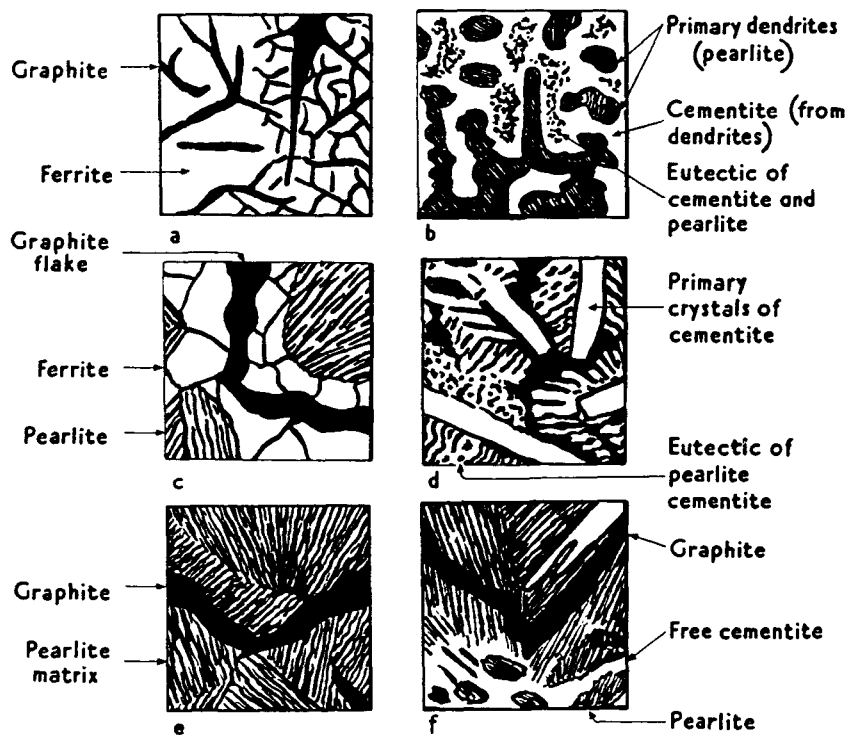


FIG. 3. Some structures of cast iron (see Rollason, 1939, pp. 189-190): 1. Free cementite and pearlite, *d* and *b*. 2. Cementite, graphite, and pearlite, *f*. 3. Graphite and pearlite, *e*. 4. Graphite, pearlite, and ferrite, *c*. 5. Graphite and ferrite, *a*.

draught, came into use, it appears that a little cast iron was accidentally produced. However, when a little cast iron was so made it would have been useless to the early smith, first, because the metal is quite unsuited to the manufacture of most tools or weapons, and secondly, without modern tools the smith would have been unable to make use of such a non-malleable material. This point is well illustrated by the care taken in working the large and high furnaces used until quite recently by some African tribes; the air-blast was carefully regulated in order not to allow the furnace to become over-heated and so to avoid the possibility of any

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liquid iron collecting in the hearth. In general we may say that in all small prehistoric furnaces the metal never collects in a fluid state in the bottom of the furnace.

In connexion with the later discovery of cast iron as a useful material, we may quote A. R. Hutchieson's remarks (1950, p. 84):

The distinction between malleable and cast iron and the purposeful production of the latter became established during the 15th century. The recent discovery of a solitary hollow 4 inch cast iron ring at Býči Skála,¹ Moravia, dating back to 600 B.C. was an astonishing revelation and pointed to an earlier knowledge of this form of the metal, but it does not prove the existence of an industry. During the 14th century, the size of the furnace used for making malleable iron had been gradually increased to save fuel and to reduce the cost of manufacture. The accidental production of molten iron had become increasingly frequent, because the metal had been kept longer in close contact with the fuel and so had become more highly carburized, which had the effect of lowering its melting point. This phenomenon, once viewed with feelings of dismay, was later to become a basic factor in the process of iron manufacture.

ROMAN CAST IRON

In prehistoric times it is agreed that the direct process was practically always used for the production of iron, but when we come to Roman times we must allow the possibility that the indirect process was known. As long ago as 1904, this question was considered carefully by Mr. May² with the help of analyses and expert advice (May, 1904, pp. 23 ff.). From smelting hearth II, at Wilderspool, near Warrington, a piece of iron strip was analysed by Mr. Ruddock, Public Analyst, Warrington, with the following result:

Carbon combined	.	.	.	.	0.060
Silicon	.	.	.	.	Trace
Sulphur	.	.	.	.	0.027
Phosphorus	.	.	.	.	0.037
Manganese	.	.	.	.	Trace
Iron, by difference	.	.	.	.	99.876

In Mr. Ruddock's opinion 'this specimen was a pure variety of soft iron made from magnetic ore or red haematite, and purified from cast iron, as such a low percentage of carbon would have been practically impossible if made direct from the ore in this rude furnace'. Again, a

¹ But in this connexion see p. 78.

² Although it dates back half a century, Mr. May's work is worthy of close study. His methods were extremely careful, and it is important to note that he took expert advice upon metallurgical questions.

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piece of wrought iron resembling a cotter or lynch pin was analysed with the following result:

Carbon	.	.	.	.	.	0.090
Silicon	.	.	.	.	.	0.060
Sulphur	.	.	.	.	.	0.031
Phosphorus	.	.	.	.	.	0.257
Manganese	.	.	.	.	.	Trace
Iron, by difference	.	.	.	.	.	99.562

The high proportion of phosphorus led Mr. Ruddock to consider that the iron was produced from an impure ore, also that it was probably made from cast iron and not direct from the ore. In view of the importance of this matter, and of the evidence found at Warrington for the use of coal for smelting during Roman times, we quote May's conclusions upon these points in his own words:

The foregoing details of (1) the construction and surroundings of three different kinds of furnaces, viz., ore roasting ovens, smelting hearths, and crucible or refining hearths; (2) two kinds of fuel, cannel coal and ordinary mineral coal in the former, and charcoal in the latter, for the manufacture of iron; (3) the results of analyses of specimens of ore, slag, cinder, crude or cast iron, and finished iron derived from these furnaces; and (4) the opinion of an expert in regard to them, are strong evidence in support of the view that an indirect method of producing crude or cast iron in one furnace, and re-heating it in another with charcoal to convert it into pure or malleable iron, was practised in this locality. This view receives further support from the discovery this season on the south side of the oppidum of another similar group of furnaces to be described later.

Concerning the use of coal as a metallurgical fuel, it is very interesting to note that mineral coal, principally cannel, was in use by the Romans at Warrington, hence the use of coal as a fuel for smelting, far from having been introduced for the first time by Dudley in A.D. 1618, must be carried back to Roman times.

It would appear that the Romans could, and occasionally did, intentionally make cast iron. Proof is afforded by the following information from Fieldhouse, May, and Wellstood (1931, pp. 12-18, p. 33). At Wilderspool near Warrington, where the 20th Roman Legion had their iron foundries, a small block of cast iron was found from one of the purifying furnaces. This iron was analysed by Mr. F. G. Ruddock, Public Analyst at Warrington, with the following result:

Block of iron about 2" x 1½" x 1", coated with scale.

Carbon combined	.	.	.	0.230 per cent.
Carbon, as graphite	.	.	.	3.000 „

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Silicon	1.050 per cent.
Sulphur	0.485 „
Phosphorus	0.756 „
Manganese	0.403 „
Iron, by difference.	94.076 „

‘A sample of cast iron extremely brittle, melted with coal from an impure ore, probably spathic, owing to the high phosphorous and remarkably high sulphur’.

Again, at Tiddington, from the Golf Links site, a bar of Roman or Romano-British iron was reported upon by Percy Rowley, B.Sc. The bar, which proved to be of cast iron, measured $6\frac{1}{8}$ in. length, the section being $1\frac{1}{4} \times \frac{7}{8}$ in., tapering to $\frac{7}{16}$ in. The weight was 1 lb. 4 oz. The analysis as given below is identical with that of cast iron commonly used in engineering practice today.

Total carbon	3.52 per cent.
Graphitic carbon	3.21 „
Combined carbon	0.31 „
Silicon	1.922 „
Sulphur	0.049 „
Phosphorus	0.765 „
Manganese	0.630 „

In the ‘settlement’ area at Hengistbury Head a considerable amount of iron slag indicated that iron smelting, probably of a poor and primitive nature, was carried on. The occupation of Hengistbury is dated by considerable finds of pottery and coins to the Iron Age and Roman periods. A most interesting piece of metal which proved to be cast iron was recovered from the settlement area. Upon this Professor Gowland (1915, pp. 76-77) reported as follows:

White cast iron. This was in the form of an irregular shaped mass, weighing about two pounds, encrusted with slag. Iron of this kind might be occasionally produced in the small primitive furnaces of the period when the temperature became higher than that required for the production of malleable iron owing to a temporary accidental increase of the blast. It is a hard, brittle metal and could not then be applied to any useful purpose. A much higher temperature is required for the production of grey iron suitable for castings, and this could not be attained in the low furnaces used for making malleable iron, so that no cast iron objects of the Roman period, or even later, until mediaeval times, have yet been found. Analyses by Mr. F. A. Harbord gave:

Carbon, graphitic	0.16 per cent.
Carbon, combined	3.33 „

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Silicon	0.38 per cent.
Sulphur	0.035 „
Phosphorus	0.180 „
Manganese	Traces „

In the light of the evidence which is now available Professor Gowland's statement to the effect that *no cast-iron* objects of the Roman period have yet been found must be modified. It is more correct to say that such objects are exceedingly rare in western countries.

In the year 1877 a statuette of iron was found by one of the workmen while digging the iron slag at Beauport Part near Hastings, Sussex. It was acquired by the late Charles Dawson who claimed that it was Roman, and probably the earliest specimen of cast iron known in Europe. The statuette was sent to Dr. Kelner of the Royal Arsenal, Woolwich, for examination and analysis, and it was found to be without doubt of grey cast iron. However, opinion was divided as to whether the statuette was really genuine. Straker (1931, p. 337) said that, notwithstanding Mr. Dawson's belief in the authenticity of the find, there are some doubts on the matter. The sale of objects found was a valuable source of income to the diggers, and it is possible that deception may have been practised. Recently, as a result of the Piltdown forgery, the statuette has again come under notice and further investigations are in progress (Downes, 1954). All we can say at the present time is that it has not yet been proved that the figure is a fake, or genuine but of recent origin. As the find was not a result of archaeological excavation it would be unwise to accept it as undoubted evidence for Roman cast iron. The Hastings statuette would be less suspicious if we could point to other small cast-iron figures of a like nature, and of Roman dating, but so far we have no supporting evidence of that kind.

In May 1883 a cast-iron statuette 15 cm. in height was dug up in the garden of a villa in Plittersdorf, Germany (Schaaffhausen, 1886). This statuette was that of an Egyptian woman and was unstratified, but in the same garden Roman tiles, sherds, and coins were also found. Schaaffhausen remarks that a Roman sculpture in cast iron has not yet been found, and therefore great care is necessary before accepting it as genuine. He points out that in the time of the first Napoleon such classical pieces were popular, and such a casting could be of recent origin. However, in his opinion there was no question of a fake, but he bases his view upon the corrosion of cast iron compared with other materials; also upon the fact that he could not trace any records to show that such figures were recently

cast in France or Germany. We cannot accept the Egyptian statuette on such terms. It is indeed more likely to be modern than ancient.

In 1846 a small cast-iron statuette of Cupid, 7.6 cm. high, was found in a field at Hockenheim, east of Speier, Germany. Schaaffhausen examined this figure in 1885 in the Karlsruhe museum. Apparently a small bronze statuette of Cupid was also found at Hockenheim, and by mistake this was illustrated on p. 141 of Schaaffhausen's paper. The correct drawing of the cast iron cupid will be found in the *Bonner Jahrbuch*, Heft LXXXII, 1886, p. 199 (Schaaffhausen). From this illustration the figure appears to be a rather crude piece of work, and could well be Roman. However, as there is no true supporting evidence of an archaeological nature, the dating must be left an open question.

In a private communication Dr. Radomír Pleiner has kindly informed me that, at Tuklaty, in the Český Brod district of Bohemia, a small quantity of cast iron of the Roman period was found at a smelting furnace. But this cast iron was only a rubbish product evidently formed by the furnace having been overheated. We then have the well-known cast iron ring (already mentioned on p. 74), from Býčí Skála, north of Brno, and now in the Vienna museum. This Hallstatt ring, if it is indeed genuine, would be evidence of the highest value. Of even earlier date, although not from Europe, is the piece of cast iron found by T. Burton Brown in his excavations at Geoy Tepe in Persian Azarbaijan, belonging to the D period which the excavator would consider to be late in the third millennium B.C. The iron has been scientifically examined (Brown and Herbert, 1950) and has been shown to be white cast iron. It is to be regarded as the rubbish product of an overheated smelting furnace rather than an intentional product.

Since the Hastings and Hockenheim statuettes cannot be relied upon, and taking into consideration the other examples which we have discussed, it is clear that the evidence for Roman cast iron in the Western World is decidedly slender. We have only the cast iron from Warrington and Tiddington reported upon by Thomas May, and the cast iron ring from Býčí Skála, and it may not be too safe altogether to rely upon this isolated find. Dr. R. Pleiner has kindly informed me that the find complex from Býčí Skála may correctly be ascribed to the sixth, or to the beginning of the fifth, century B.C., and classified as of Horákov type (or better as of Podolí type), of the south Moravian Hallstatt group. However, in Dr. Pleiner's view, the circumstances of the actual finding of the ring are not certain. Other cast irons reported appear merely to be the

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chance products of overheated smelting furnaces and therefore do not furnish evidence for the intentional production of iron as a cast material.

Again, it is suggestive that Dr. Otto Johannsen (1954, pp. 21-29) in his monumental work upon the history of iron does not appear to consider the possibility of Roman cast iron as of importance, nor does he mention Roman statuettes or other cast-iron objects of archaeologically proved context. From the evidence at present available to us, we can only say that cast iron apparently sometimes was made during Roman times, but that it was extremely rare, and of no importance to the iron industry until many centuries had elapsed.

CAST IRON IN CHINA

In China cast iron occupies a special place, and one of very considerable importance. Professor J. Needham, F.R.S., has very kindly furnished us with advance information and references from *Science and Civilisation in China*. In Professor Needham's view, it is generally agreed that iron came relatively late to China. No one would put it before the eighth century B.C. and the general view among western sinologists has been that the first reference to the metal is of 512 B.C. when a legal code was inscribed on cauldrons made of iron (Couvreur, tr. of *Tso Chuan*, vol. iii, p. 456). The strange conclusion emerges that the Chinese could cast iron almost as soon as they knew of it, for the technical term used (*chu*) means unmistakably that. Some argue that the word is a misreading, but others strongly disagree. If the *Tso Chuan* reference is laid aside, the next reference is probably that in *Mencius* (Legge, tr., p. 124), i.e. late fourth century B.C., where again a word (*yeh*), having definite implication of casting and pouring liquid metal is used. After that comes considerable evidence. Professor Needham has drawings of late Chou cast-iron agricultural tools which were excavated from tombs at Huihsien. If these tools really are of cast iron, which Professor Needham thinks possible, they antedate the Han iron dating from about A.D. 200 and described by Laufer.

When one comes to the Northern Wei period iron statues become plentiful; some are dated from the fourth to sixth centuries A.D. In later times great skill and ability were shown by the Chinese in iron castings of enormous size. What must be the earliest example of the use of cast iron as a building material is a most original application of the metal to pagodas. From Professor Needham we have the following special note on cast-iron pagodas:

A remarkable development of pagoda building was that which made them of

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cast iron, or more often of bronze. The oldest existing iron pagoda, at Yü Chhüan Ssu at Tangyang in Hupei, which dates from +1061, is of very considerable size, being 70 feet high and having thirteen storeys. It is said to weigh 106,000 pounds. Another smaller one of nine storeys is at Kan Lu Ssu at Chenchiang in Chiangsu. Local tradition dates it from the time of Li Tê-Yu, the famous geographer and minister of State (+787/+849), who founded the temple, but more probably it was set up by Phei Chhü (+1078/+1086). Yet another, at Chhung Hsueh Ssu at Tsining (Shantung), has eleven storeys. Smaller ones in bronze are quite numerous.

Professor T. T. Read (1937, pp. 30-34) mentions a very large iron casting of a lion standing in the yard of the Kai-Yuan monastery, Ts'ang-chou. This enormous hollow casting is about 20 feet high and 16 feet long. The metal walls vary from $1\frac{1}{2}$ in. to 8 in. in thickness. It is made in one piece by pouring small sections of it at a time and the weak joints between the sections are quite evident. Such weakness would not greatly matter in the case of a religious art statue of this nature for it would not have to be moved, and therefore mechanical strength would not be an important consideration. Read says that there can be no doubt as to the date of this casting, A.D. 953, since, like a modern bridge or public building, the date was placed on it when it was made. In this connexion we may note that Read (op. cit., p. 31), says that:

In the course of a recent visit to China search was made for smaller and earlier iron castings which bore an inscription shewing the precise date at which they were made, and a number were discovered; some bearing dates as early as 500 A.D. As might have been expected, these were mostly of a religious character since any ordinary object would be likely to be broken up and remelted when it became old and obsolete.

No iron casting bearing a date earlier than A.D. 500 came to Read's notice, with the exception of one which he considered as spurious. Without due investigation it is clear that a date cast upon the object cannot always be accepted as genuine, particularly in the case of the smaller castings. As Read considered one such date to be spurious, there may well be others of a like nature.

In an earlier paper, Professor Read (1934, p. 547) refers to the following iron castings:

At Pingtingchow, Shansi, there is a large cast iron bell, which is dated 1079 A.D. At Chin-ssu, 10 miles south-west of Taiyuanfu, Shansi, there is an iron statue, larger than life-size, which is dated by the inscription on it as having been cast in the year 1097 A.D. Four similar statues at a temple at Tengfênghsien, Honan, are definitely dated 1213 A.D. In the 'Thousand Buddha Hall' of the

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Hsuan-chung-ssu, about thirty miles south-west of Taiguanfu, there were in 1920, two hundred and twenty-five cast iron Buddhas, each about 30 inches tall. A stone in the wall of the hall gives the date 823 A.D. but B. Tokiwa (1926, pp. 2-3) thinks from their appearance that the statues were cast in 960-1127 A.D. In the same temple there is a stele that says, *inter alia*, that a man named Chan donated an iron statue of Maitreya to the temple in 738 A.D.

In the prehistoric period in China, it is difficult to be certain of the authenticity of cast iron. We may cite the famous Chinese iron stove which some have mentioned as 'probably the oldest cast-iron object still extant'. The stove is not archaeologically attested; Laufer (1917, pp. 79-80; pl. ii) obtained it from a dealer who stated that it came from a Han grave. However, Laufer did not see the grave and said himself that, while there is probability in assigning such cast-iron objects to the Later Han (A.D. 25-220), it is equally justifiable to extend the time of their manufacture over the entire third century of our own era. On such evidence, one can hardly accept the lower dating and, in view of its decidedly sophisticated appearance, may not such stoves belong to a far more recent period than that put forward by Laufer?

In 1910 Professor Read (1934, pp. 550-2) visited the iron district of Pingtingchow, Shansi, to observe metallurgical methods and to collect specimens. He found that iron castings were being produced by the ancient methods. The iron ore was mixed with coal and reduced by a crucible process in a natural-draught furnace, the product being a spongy bloom of wrought iron, and many smaller particles of iron. The malleable bloom was worked up into the usual objects of wrought iron; the smaller pieces of iron were again packed into crucibles with Shansi coal, and converted to cast iron in a forced-draught furnace. Read noted that the iron ore used contained only $\frac{1}{2}$ to 1 per cent. of phosphorus. The cast iron made from such an ore in the ordinary way would not contain over 1 per cent. of phosphorus, but the finished castings contained from 5 to 7 per cent. The additional phosphorus can only have been taken up from the Shansi coal used in the crucible process, and by an additive which the workmen called *hei-tu*, which was associated with the coal and contained crystals of vivianite (iron phosphate).

Iron containing phosphorus in the region of 7 per cent. would melt at 980 to 1,000° C., that is, at an even lower temperature than that required to melt copper. If the early Chinese iron founders used the technique observed by Read in 1910, we have a good explanation of why they were able to cast in iron with apparent ease. According to Read the few

analyses of early Chinese cast iron do not show a high phosphorus content, so that the answer may lie rather in the low sulphur content of the Shansi coal which would render it a suitable fuel for smelting. Sulphur in the fuel is extremely harmful, and in England it was not until the eighteenth century A.D., when it was learned how to coke the coal, that this fuel replaced charcoal in the smelting furnace.

Concerning the composition and structure of ancient Chinese iron castings, Pinel, Read, and Wright (1938, pp. 174 ff.) examined the following specimens:

- (1) 502 A.D. Two recumbent lions, 26 lbs. each. Date cast on.
- (2) 508 A.D. Two ink slabs, $4\frac{1}{4}$ lbs. each. Date cast on.
- (3) 550 A.D. Kwan Yin (Goddess of Mercy). 50 lb. Date cast on.
- (4a) 558 A.D. Kwan Yin. 16 lbs. Date cast on.
- (4b) 719 A.D. Panel showing Buddha and two attendants. 52 lbs. Not analysed.
- (5) 923 A.D. Two panels with Buddhist figures. 25 lbs. Date cast on. One analysed.
- (6) 953 A.D. 20×16 foot lion.
- (7) 1093 A.D. One of 1024 cast iron panels. $7\frac{1}{4}$ in. \times $7\frac{3}{4}$ in. 6 lbs. From a pagoda.
- (8) 'Flying scissors' ? 300 A.D.
- (9) Stove. ? 200 A.D.

Numbers 1 to 4a, 4b, and 5 have dates, even to months and days, cast on them. It appears that these pieces were bought by Read from a dealer in Nanking for so low a price that no one could have made them for profit as copies of originals. It is interesting to note that the metallographic study showed a wide diversity of structure, white, grey, and mottled irons, with relatively low phosphorus contents. Castings 1 to 5 were of grey iron, numbers 1 and 2 having a pearlitic structure, and the others containing ferrite in various amounts. Numbers 6 to 9 were white or mottled cast irons, numbers 6 and 9 being somewhat similar except for the presence of some mottled iron areas in number 6. Whereas the latter were hypereutectic, number 7 was definitely hypoeutectic. Number 8 was a mottled iron structurally between grey and white irons. Numbers 1 to 5 of grey iron were cast in sand moulds which, if their dating is reliable, furnish an early example of the use of sand moulding; the variations in the structure and analyses of each of the castings tend to confirm their authenticity, but naturally cannot be taken as proof of the dating put forward.

To the western metallurgist of today, the idea of such early production and utilization of cast iron by the Chinese is indeed strange and only to

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be accounted for by special conditions of fuel, ore, and smelting. These conditions we have already remarked upon. Again, as Professor Needham has pointed out, a factor which must greatly have helped in the success of the conversion process is the antiquity in China of the double-acting

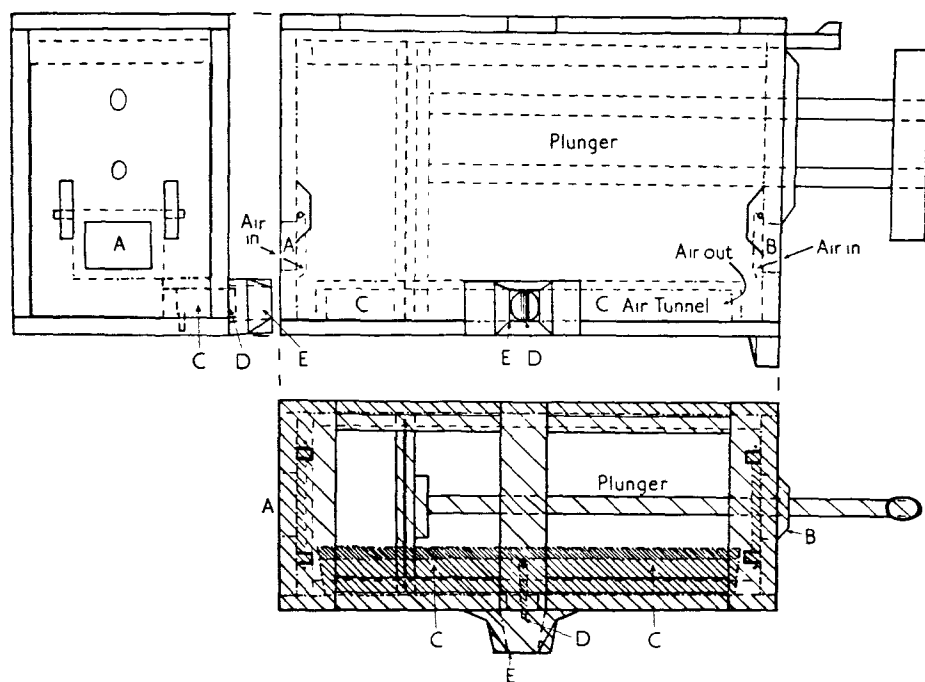


FIG. 4. Double-acting piston box-bellows from the Tibeto-Chinese border. Coll. by Sir A. Hosie, 1908. Pres. by Lady Hosie, 1934. Pitt Rivers Museum.

Withdrawing the plunger decreases the pressure on valve *A*, thus allowing the left-hand side of the chamber to fill with air; at the same time the air in the right-hand side of the chamber is compressed and forced through the air tunnel *C* which contains a tongue *D*. This automatically swings to the left allowing the air to pass out of the mouth *E*.

Reversing the direction of the plunger causes valve *B* to open, thus allowing the right-hand side of the chamber to refill with air. The air in the left-hand side of the chamber is compressed and forced through the air tunnel *C*. The tongue now swings to the right, allowing air to flow again through the mouth *E*.

If this oscillating motion is maintained, an almost constant pressure of air is obtained.

piston bellows which give a continuous blast (Fig. 4), and so would render the attainment of high furnace temperatures a relatively easy matter. Professor Needham's recent findings concerning the ancient and mediæval Chinese iron and steel industry are of extreme interest and importance. We have been favoured by the Professor with the following brief

résumé of his research, the full account of which will in due course be published in *Science and Civilisation in China*, vols. 6 and 7, now in course of production by the Cambridge University Press.

- (A) In China iron seems to have been known only from the 6th century B.C. onwards. Presumably the first product was bloom wrought iron, in 'Catalan' style.
- (B) Cast iron appears from the 2nd century B.C. onwards, probably made by a crucible process. Factors connected with this early appearance probably were:
 - (a) High phosphorus ores, or the addition of small amounts of high phosphorus minerals.
 - (b) Availability of good refractory clays.
 - (c) Coal, used from at least the 4th century A.D. onwards, perhaps long before (permitting a very hot pile, the sulphur being excluded by the crucibles).
 - (d) The double-acting piston bellows from the 2nd century B.C. onwards, certainly in the 3rd century A.D. made of bronze with iron tuyères.
 - (e) Application of water power to these as early as the 1st century A.D.
- (C) Steel was produced, presumably by cementation, in Chou and Chhin (i.e. before the Han dynasty, starting in the 2nd century B.C.), from the blooms, and probably later from wrought iron puddled from cast iron.
- (D) From the 5th century A.D. onwards at least, the Chinese made steel by co-fusion of cast with wrought iron, almost certainly by a crucible process.
- (E) From the 5th century A.D. onwards at least, they were also able to make steel by heating and forging lumps of cast iron between faggots of wrought iron.
- (F) By the 11th century A.D. at least, they made another class of steel by direct cold-blast decarburisation of cast iron, forging with air-stream till no further decrease in weight. As this steel was preferred, its carbon content was perhaps more uniform.
- (G) In addition, some Wootz steel seems to have been imported from India from about the 5th century onwards.
- (H) The forging together of hard and soft steels to make weapon blades seems to have begun in the 3rd century A.D. in China, and to have been transmitted in the 7th century A.D. to the Japanese, who in later times brought it to a great art.

To sum up, it seems doubtful that cast iron in China is so early in origin as some authorities would consider to be the case. However, it appears possible that the Chinese made serious use of cast iron from around A.D. 500, and established what may almost be called a heavy industry by A.D. 1000, in which case they would have been far in

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advance of the Western World where cast iron was not widely or seriously used in any form prior to the fifteenth century A.D. Also, if we may accept the dating put forward for the Kai-Yuan lion, and the Yü Chhüan Ssu pagoda, the Chinese were the first people in the world to produce heavy iron castings on what may well be called an extensive, and even commercial, scale.

Chapter V

FURNACES AND FUELS

THE SMELTING FURNACE

To follow the evolution of the iron-smelting furnace is a difficult matter. First, the number of iron furnaces which have been found and excavated is not very great; also it is exceedingly unfortunate that evidence from the Ancient Near East is scarce and far from satisfactory. No doubt the Near East contains the cradle of the earliest iron working and a type series of smelting furnaces from these lands would be of the highest value. Unfortunately, so far such evidence is lacking. Another difficulty is that the fairly numerous furnaces found in Europe seem, according to the published reports, to represent a confusing number of types. It is unusual for a furnace to be found by the excavator in good condition, and all too often the upper portion is entirely missing. Under such conditions it is extremely difficult for an archaeologist to attempt any reconstruction of the furnace type unless he has guidance from an expert upon early furnaces. Even advice from a practical foundry man would have prevented some of the misleading, and even absurd, theories and reconstructions from which European furnaces have suffered much in the past. Further research will be required before we can present a clear picture of furnace evolution from the simple bloomery hearth up to quite advanced mediaeval designs. The most simple and primitive furnace is, of course, the bonfire. We need not consider this simple device for, although it may well be possible to smelt such an ore as cassiterite, the tin ore, in a simple bonfire built at ground level, because the reduction process requires but low temperature, such a furnace would not be applicable to iron smelting where a much higher temperature, combined with control of the atmospheric and other conditions in the furnace, is required.

It is natural to consider that the original iron-smelting furnace was of a simple nature, but before we can be certain of this we require dated examples of furnaces which may safely be ascribed to the earliest phases of iron smelting. A further complication arises from the fact that in many regions there must have been a long tradition of copper smelting behind that of iron working. Hence, the iron smelter may well have had the

advantage of a series of sophisticated copper-smelting furnaces behind him. We may here quote Professor R. J. Forbes's remarks (1950, pp. 405-6):

The beginnings of the iron industry are still very dark from the technical point of view. All we can say is that the earliest bloomeries must have consisted of very simple clay-lined pot-bowl furnaces or simple bloomery fires (*Rennfeuer*) both worked with blast air and smelting ores of the limonite and ochre type or weathered haematite. We have seen that these simple furnaces developed into the peculiar shaft furnaces called 'Stückofen' by the way of the Catalan hearth, and how these Stückofen permitted the smelting of ores of the haematite and magnetite type. But the early iron industry will remain dark as long as the history of the smelting furnace is not known better in detail.

There is little point in trying to work out an elaborate series of furnace types which can only be based upon vague and often unreliable theories and reconstructions. Until much more excavation and research have been carried out it is wise to confine ourselves to major groups which are founded on good evidence. There appear to be three well-established types of early iron-smelting furnaces:

- (a) The simple bowl furnace.
- (b) The Domed furnace (sometimes called the Pot furnace).
- (c) The Shaft furnace.

Again, there is a major distinction between furnaces worked with the aid of a forced draught, and those which rely upon natural draught alone. It by no means follows that the use of bellows to provide a forced draught in the iron-smelting furnace indicates a higher technique. While bellows-blown furnaces were used at a very early date, around 1500 B.C., in Egypt, there is evidence to indicate that some form of bellows and air-blast was known in Mesopotamia as early as the middle of the third millennium B.C. (Coghlan 1951, p. 69). On the other hand, natural-draught furnaces were used in the prehistoric Iron Age of Europe, in the Middle Ages, and even later. In some cases it is easy to tell if a given furnace belongs to the forced, or natural-draught, type. In built-in furnaces, such as those of Siegerland, where there was but one entry—the wind passage—natural draught was relied upon. On the other hand, furnaces such as those of Einzingen and Tarxdorf certainly used forced draught. It is not so easy to determine the question when the furnace excavated is in bad condition, or when sufficient of the furnace does not remain to allow of an accurate reconstruction. Here, it may be possible

by an examination of the slag to estimate whether it belongs to a blown- or a natural-draught furnace. Again, when tuyères of baked clay are found in association with the furnace, there is strong evidence for the use of a bellows and air-blast. It must, however, be remembered that (as in the case of some modern primitive African furnaces), a number of clay tubes spaced round the lower part of the furnace may be used to provide, or to regulate, a natural draught. Conical tubes or tuyères point to the use of the bellows rather than do cylindrical ones. Also, cylindrical tubes which are long enough to pass through the wall and lining of European furnaces do not, as yet, appear to have been recorded.

For iron smelting the bowl furnace was simple and widely used. As the name indicates, it consisted of a bowl-shaped hole in the ground, lined with clay which baked to a hard and fairly smooth surface. Artificial draught would appear to be necessary with this type of furnace and was probably provided by means of a bellows and blast-nozzle or tuyère. The charge of fuel and ore would be built up in the form of a cone, or dome, above the level of the top of the bowl, while the pipe leading from the bellows to the blast nozzle would pass over the rim of the bowl as indicated by Neuburger (1930, fig. 23) for the Kordofan bloomeries. It is by no means certain that this somewhat awkward arrangement of leading in the blast air over the rim of the bowl was the method most generally employed; the air-supply could have been introduced at a lower level with advantage. It is also doubtful whether means for tapping the slag were used in connexion with the early bowl furnaces. The bowl furnace was not an efficient one; there would be a very serious loss of heat from the open top of the fire, and there must also have been a very considerable loss of iron to the uncontrolled slag, but the simple bowl had a very long life and seems to have lasted on from prehistoric times into the Middle Ages. It is also known from modern primitive contexts. Again, it is early known in Egyptian paintings, and Oliver Davies (1935, p. 43) quotes various known finds in Europe. Professor Gowland stated that the bowl furnace was associated with Roman pottery in the tin workings of Cornwall (1899, p. 299). At Hüttenberg in Austria, interesting installations of bowl furnaces set in a stone pavement were discovered (Weiershausen 1939 p. 157). The installations were in pairs (Fig. 5, after Weiershausen Abb. 42), and it was thought that one of the bowls was used to roast the ore prior to the smelting operation in the other. It is not certain that a roasting process was, in fact, in operation at Hüttenberg. The second furnace may equally have been used for reheating to refine

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the bloom after smelting. Evidence is lacking to show the method adopted for the necessary air-blast, and no passage which would have served to tap the slag was reported by the excavator.

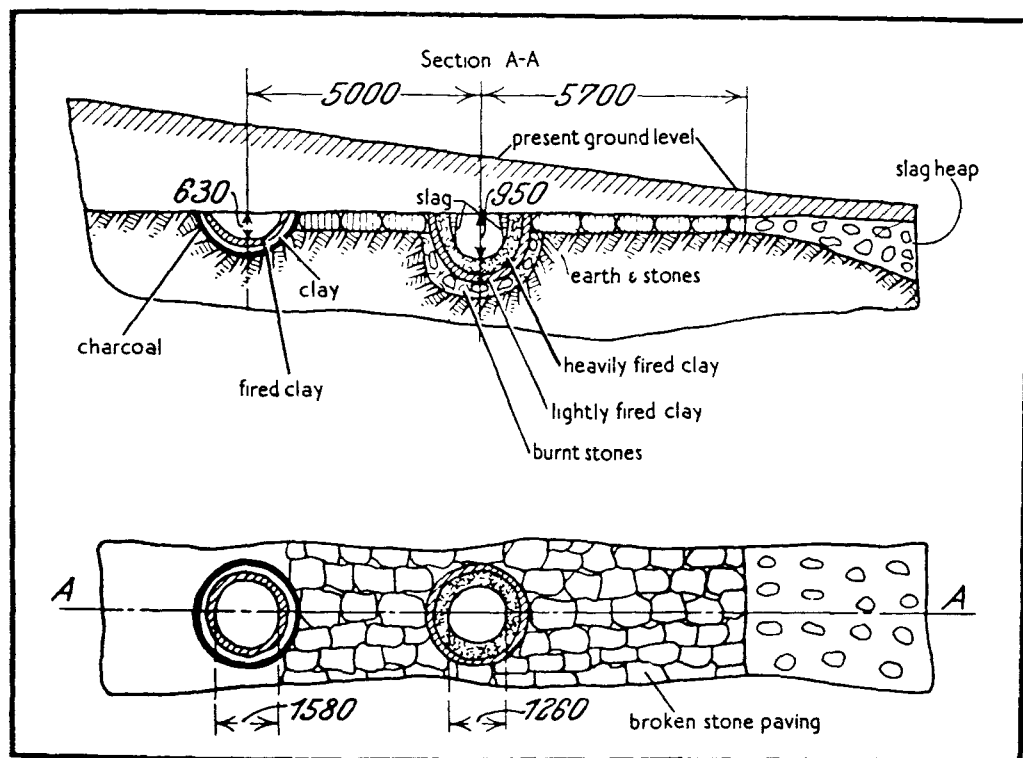


FIG. 5. Bowl furnaces at Hüttenberg in Austria (Weiershausen 1939, Abb. 42).

THE DOMED FURNACE

We may now consider that very important type, the domed furnace. Such furnaces have sometimes been called 'Pot' furnaces, but in the author's opinion 'Domed' is the better term since a pot may take many forms but a dome remains a dome. The type may quite possibly be a variant of, and developed from, the bowl furnace, but it may also owe its origin to the pottery furnace, for domed pottery kilns were in being long before the dawn of the Iron Age. The major constructional feature, the dome, may well have been borrowed from the older pottery kiln. In construction the furnace is simple; the circular hearth may be flat or hollowed to a dish-like form. Smelting is carried out in the domed chamber above the hearth, with a central chimney to carry off the

products of combustion. These furnaces may be built-in on the side of a hill, or they may be free standing. In general, the domed furnace of the European Iron Age relied upon natural draught.

Excellent examples of Iron Age domed furnaces for iron smelting were discovered from 1930 onwards in Gosenbach, Kr. Siegen, south Westphalia (Stieren 1935, pp. 12-20). The Siegerland finds revealed the existence of an important iron-smelting industry; in all, some ninety pre-Roman slag heaps and smelting sites were recorded. The pre-Roman furnaces belonged to the La Tène period of the Iron Age and were late rather than early in the period. They had clearly a very considerable tradition behind them. Furnaces built into the side of a slope and free-standing furnaces were found. The free-standing ones were in general similar to the built-in type, but the wind passage was omitted as air could enter all round, a number of wind or draught holes being provided round the base of the furnace. A reconstruction due to Krasa is given in Fig. 6 (from Weiershausen Abb. 2). Furnace number E. 25 in the Engsbachtal was in such good preservation that a complete reconstruction was possible. Both built-in and free-standing furnaces appear to have been in use at the same time. In the Engsbachtal furnaces the dome was roughly 1 metre in diameter and 1 metre in height, the dome had a low chimney for charging and escape of the combustion gases, and air was supplied by means of a tunnel or wind passage. The body of the furnace was built of clay and sometimes the floor of the hearth was of flat stones. In furnace E. 25 the wind passage was about 2 metres long and of square section, 30 to 40 cm. inside. Stone slabs were used to line the passage. A most interesting feature of these furnaces is that the wind passage is provided with nozzles or tuyères at the hearth end, one to three nozzles of from 6 to 8 cm. in diameter being used. Natural draught must have been relied upon for the operation of the furnace and it was evidently realized that, when a good wind was blowing into the wind passage, the velocity of the air could be much increased by the provision of tuyères, so obtaining a more intense heat in the furnace. In other words, the smelter combined natural draught with the principle of the bellows.

In recent years a most important work has been accomplished by Weiershausen (1939), who has studied what is known of the European furnaces, and has shown where certain reconstructions and theories cannot be accepted from the technical point of view. We may now notice some of the more important furnaces dealt with in his work. An important furnace, because sufficient remains were found to permit a reconstruc-

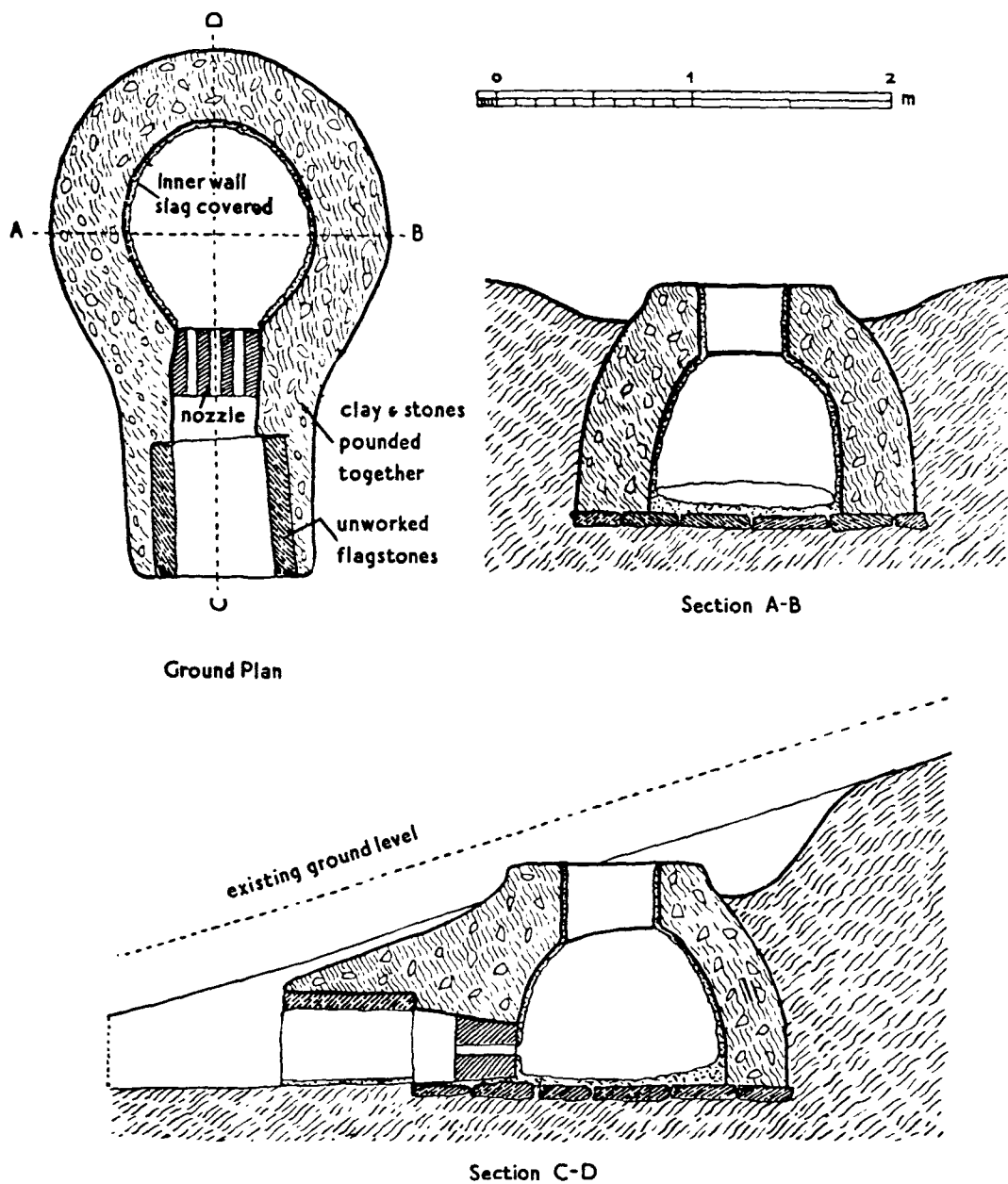


FIG. 6. Engsbachtal domed furnace, No. E. 25. (Weiershausen 1939, Abb. 2.)

FURNACES AND FUELS

tion, is that of Aalbuch, about 1 kilometre to the south of Tauchenweiler, in Württemberg, south Germany (Fig. 7 after Weiershausen Abb. 12). The furnace is of large size and is unusual in that it may have been built

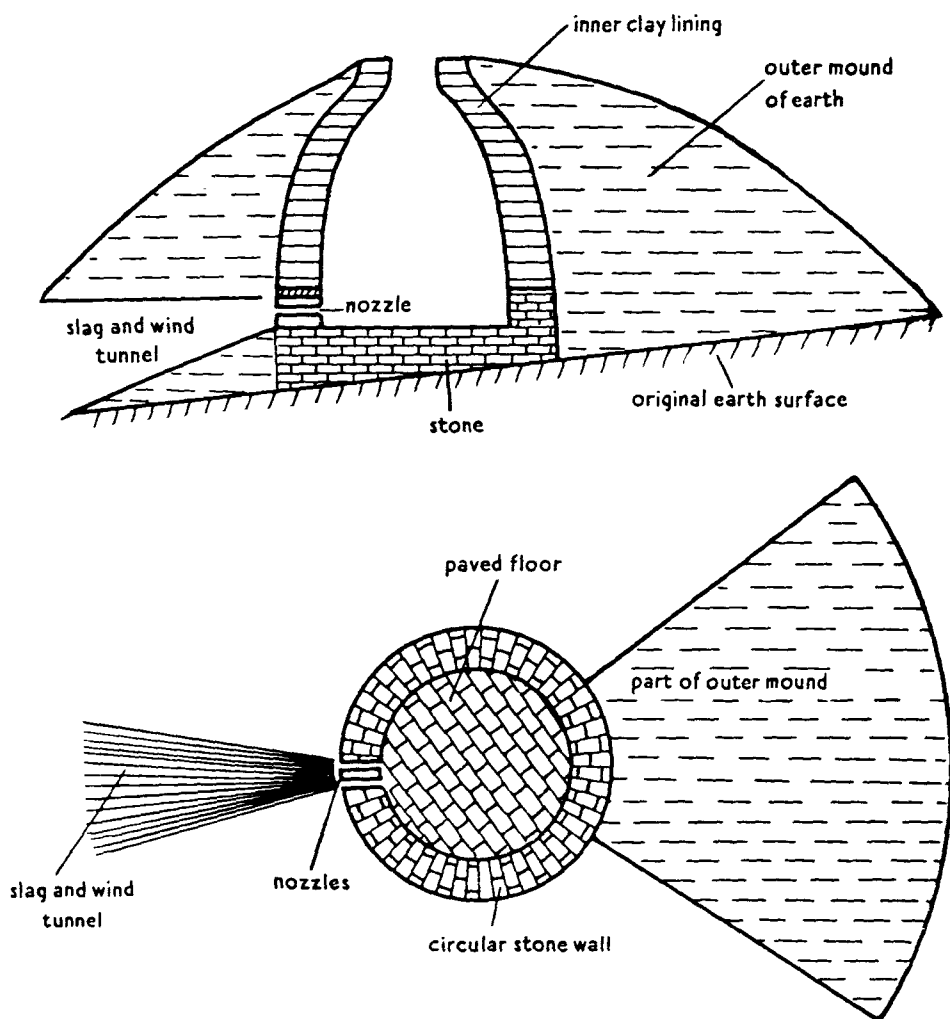


FIG. 7. The Aalbuch furnace (Weiershausen 1939, Abb. 12).

into a round barrow. Unfortunately dating material was absent, but it seems a typical La Tène furnace, and should belong to that period. The mound which contains the furnace is 8.5 m. in diameter, and 1.7 m. in height (Weiershausen 1939, pp. 66-69). The furnace was carefully built, a circular stone floor being laid down, and upon this was built a

stone ring-wall to a height of approximately 25 cm. The circular hearth was 1.7 m. in diameter. The furnace dome closed in from above the stone ring-wall to the usual contracted chimney or smoke opening. The smelting was carried out under natural draught, for which a westward-pointing combined slag and wind passage was provided. This passage apparently ended at the furnace-hearth with nozzles or tuyères as in the Siegen furnaces. The Aalbuch furnace is important as an example of an Iron Age furnace of considerable size operated under natural draught. The arrangements for withdrawing the bloom are not clear. The nozzles or tuyères may have been broken-out or otherwise removed after each smelt, but it cannot have been easy (if indeed possible) to withdraw the bloom and make good the nozzles in the small and lengthy wind passage shown in the reconstruction. In this case, we should be strongly inclined to the view that there must have been some other means of access to the furnace hearth, or that the wind passage must have been of larger dimensions than indicated by the reconstruction.

As an example of how easily confusion in furnace typology may arise, the furnaces of Tarxdorf, in Silesia, east Germany, may be mentioned with advantage (Weiershausen 1939, pp. 97-104, and figs.). These furnaces, of which there were apparently a great number, are very difficult to explain. The reconstructions put forward by Krause, Giebeler, and Humperdinck do not agree in all respects. Only the bottom portion of the furnaces which was below the present ground level was found, and it appears decidedly questionable if an upper part ever existed. The descriptions of the above mentioned authors would indicate the production of cast iron which is certainly incorrect. The date of the Tarxdorf furnaces does not appear to be well defined, although Hallstatt pottery was found. Bog-iron ore seems to have been smelted, and according to Weiershausen there is no need to consider that there was any upper part to these furnaces. Nothing of the sort was, in fact, found. It is more likely that the furnaces were of the free-standing bloomery type with a combined wind and slag passage, and that they would have produced the normal wrought iron. Krause and Giebeler have surrounded the Tarxdorf furnaces with complex theories which are technically impossible. Weiershausen's view that the furnaces are quite ordinary bloomery ones would appear, in the light of his technical explanation, to be acceptable and in all probability correct. Before the Tarxdorf furnaces can be brought into their correct typological place there is need for further examination and report by an expert technologist.

A well-preserved iron furnace of pre-Roman date was excavated at Krampniss in east Germany, by Bestehorn (Weiershausen 1939, pp. 123-33, and Figs. 31, 32). An important feature was that the iron working was carried out through the use of two furnaces, No. 1, which Bestehorn termed a reverberatory furnace (*flammofen*), and No. 2, a crucible furnace (*Tiegelgrude oder Tiegelschmelz*). The so-called *flammofen* is of great interest and quite advanced construction. Steps led down to a stokehold and firebox, and the firebox communicated by means of a duct with a domed chamber like that of the conventional domed smelting furnace. Hence, the furnace consisted of two separate chambers, but in each chamber a charcoal fire was operated. The so-called crucible furnace, No. 2, was considered by Bestehorn to be a pit in the ground containing a charcoal fire upon which the crucible was placed. According to him the operation of the complex was that an impure bloom of iron was produced in the domed smelting chamber of the *flammofen* No. 1, this bloom was next submitted to a crucible process (but not to crucible smelting), in the crucible furnace No. 2. For this purpose the bloom was placed along with charcoal in a clay crucible which was heated over a charcoal fire in the crucible furnace until the iron was refined and rendered of forgeable quality. During the process the iron would absorb carbon.

Weiershausen does not agree with this sequence and thinks that the so-called crucible furnace was in reality a forced-draught smelting furnace in which the iron was actually produced. He considers that there is no evidence to prove that a crucible existed, and that the pieces of the alleged crucible which was found were merely broken pieces of the inner lining of the smelting furnace. In the *flammofen*, No. 1, Weiershausen would see a furnace for converting the iron bloom into steel, or semi-steel. If correct, this is most important, for it gives us an example of a special furnace used for the conversion of wrought iron at an early period. It is not correct to term the conversion furnace a *flammofen*, or reverberatory furnace, because fuel was burnt in both chambers, and the same chimney draught applies to each. The firebox is really a pre-heating chamber, the charcoal fire in which was for pre-heating the charge and walls of the second or domed chamber which contained the wrought-iron bloom to be refined, and a second charcoal fire. In such early furnaces pre-heating of this nature would be most desirable, and possibly necessary in order to attain the temperature required to ensure an adequate increase in the carbon content of the iron under treatment. Pre-heating is, of course, a very common technique with the modern furnace. It also seems

to have been known and used in some peasant smelting furnaces of the Middle Ages in Germany. Weiershausen's theory appears to rest on a sound technical base. If the *flammofen* was merely a smelting furnace as thought by Bestehorn, there is no need for its elaborate design in view of the early dating of the furnace. On the other hand, as a refining or steeling furnace, the reason for its construction at once becomes clear.

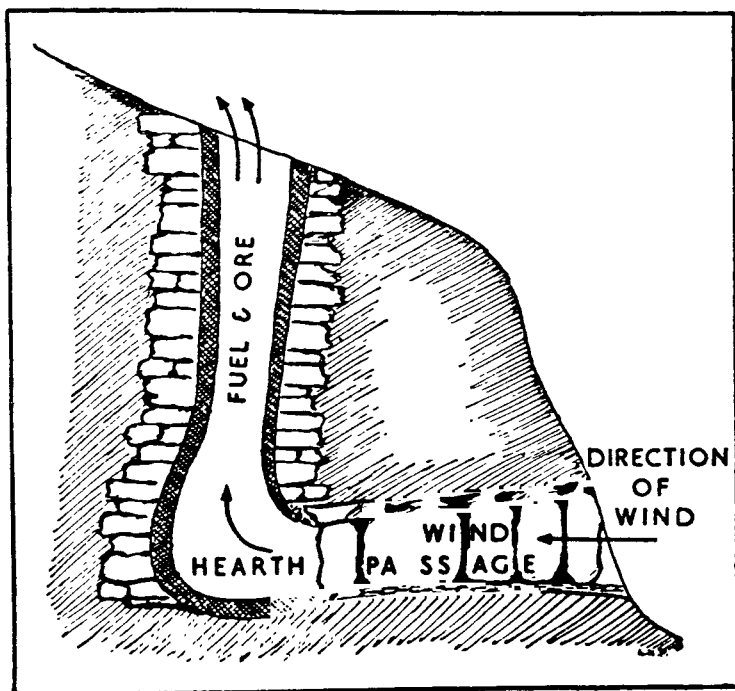


FIG. 8. The Jura Type shaft furnace (Coghlan 1951, Fig. 6).

THE SHAFT FURNACE

With the shaft or Jura type of furnace we come to a well-developed and important type. In its developed form the construction resembles a chimney shaft lined with baked clay with a wind passage leading into the bottom of the shaft (Fig. 8, Jura type). Such furnaces can be worked with natural draught. In the Jura furnaces the wind and slag passage is combined. Also, the bloom would have to be removed through this passage. Fuel and ore could be charged down the chimney while the furnace was in blast so that something like continuous operation may have been possible. In the shaft furnace we see the idea of the modern furnace, but unlike a modern coke-burning installation, the primitive

shaft furnace was limited in height by the nature of the fuel used, for charcoal fuel is not sufficiently hard to withstand heavy loads of ore such as occur when the furnace height rises beyond some 15 to 20 feet. As well as in the Jura, shaft furnaces have been found at Mitterberg and Velem St. Veit (von Miske 1929, p. 81). According to Oliver Davies shaft furnaces were apparently used at H. Sosti (Siphnos), in the sixth century B.C., and were in regular use at Laurium and in Etruria, while in Roman times the shaft furnace had become known in most provinces. The distribution of the type became wide and it had a long life (Davies 1935, pp. 44-48).

We may obtain some idea of the capacity of and mode of working these furnaces by analogy with the modern primitive shaft furnace from Burma which is mentioned by Gilles (1936, p. 256, Abb. 4). This furnace was over 10 feet in height and depended for its action upon natural draught alone. In the Burmese furnace the short but large wind passage terminated in no less than twenty tuyère tubes, each of 5 cm. in diameter. The furnace charge comprised about 210 Kg. of ore, and 219 Kg. of charcoal. After eight or nine hours the slag was tapped, and then tapping of the slag was carried out at intervals. After twenty-four hours an opening was made in the bottom of the furnace, and the smelted bloom of iron, weighing some 45 Kg., removed. With this, it is of interest to compare Richardson's (1934, p. 576) estimation of the yield of the smaller iron furnaces. He says:

Like its copper smelting prototype, the Hallstatt furnace would be a shallow excavation, about two feet square and deep, lined with refractory clay. But where this excavation had formerly comprised the entire unit it was now merely the hearth; the smelting chamber proper rose above the ground to a height of two to three feet. Its inner wall, banked with sod, was enclosed by a rough stone facing, possibly twelve inches square at the top. This chamber gradually widened to twice that dimension at the hearth, into which a free-flowing stream of air was admitted through an opening pointed into the wind. Furnaces of this type might conceivably produce in eight to ten hours a semi-fused mass of iron weighing fifty pounds. In this operation alone approximately two hundred pounds of charcoal would have been consumed, while subsequent heating and working required at least one fourth as much more.

Of shaft furnaces, apart from those of the Jura type, that found at Lölling, in Austria (Weiershausen 1939, pp. 161-2), is highly important, for it gives us a plan and section of a furnace which was recovered practically in its original condition (Fig. 9, after Weiershausen's Abb. 44). This is a shaft furnace, with a shaft 1.26 m. in height (possibly

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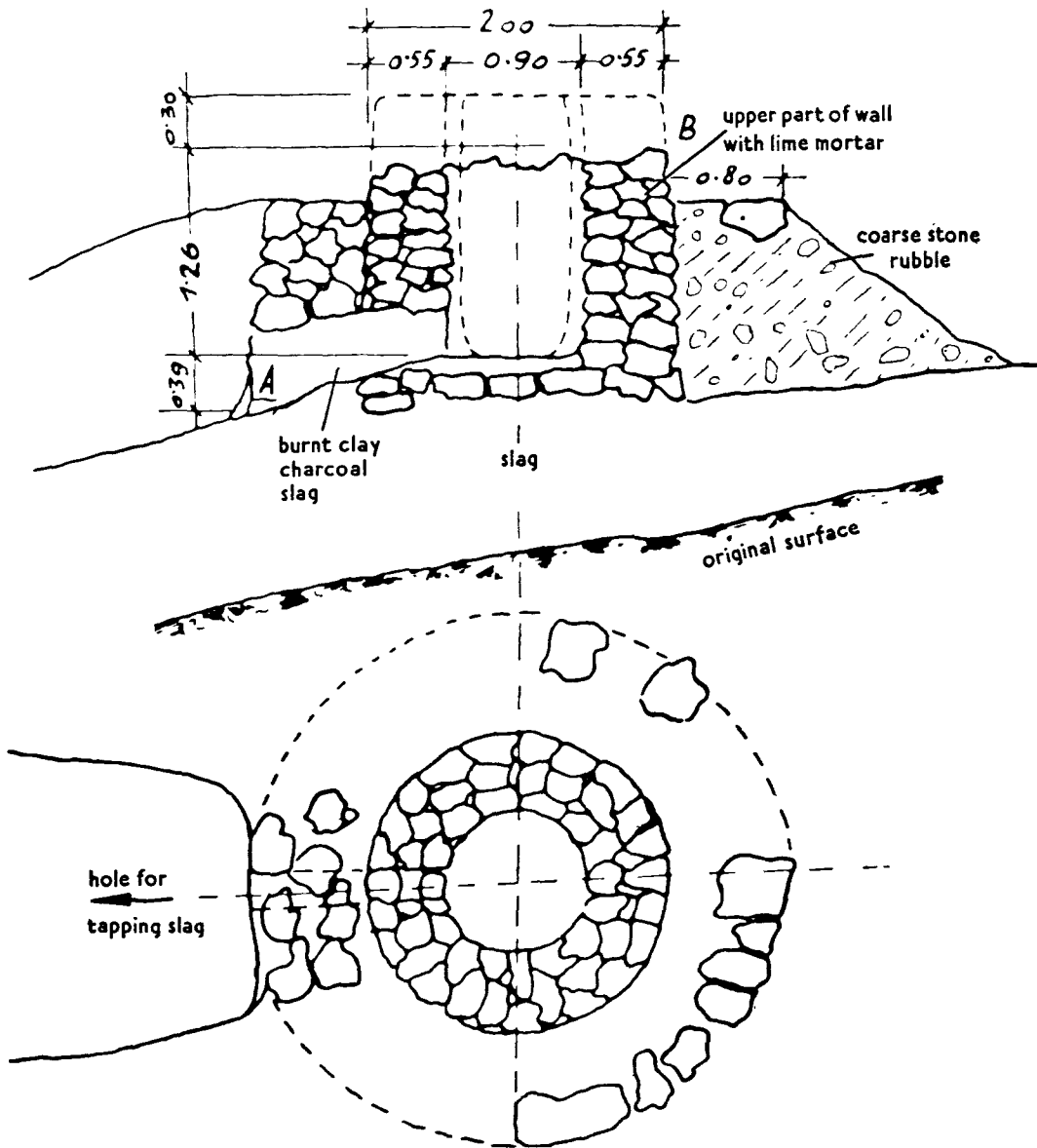


FIG. 9. The Lölling shaft furnace (Weiershausen 1939, Abb. 44).

originally slightly higher), and 90 cm. internal diameter. The shaft was built up in dry stone walling and the whole surrounded by a rubble mound. Originally the shaft and furnace pit were lined with baked clay as an insulating material. At one side of the furnace is a passage through which the slag was tapped, and on the drawing this passage resembles a

FURNACES AND FUELS

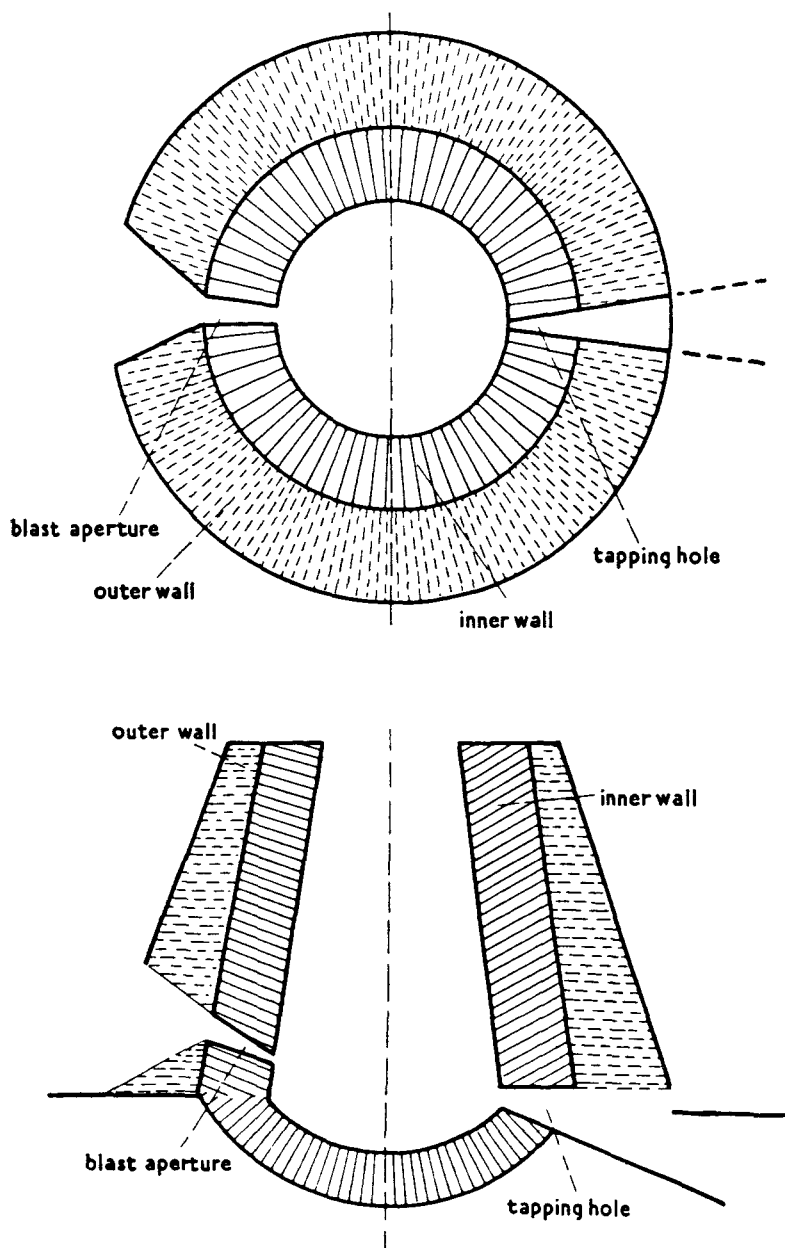


FIG. 10. The Eisenberg shaft furnace (Weiershausen 1939, Abb. 17).

wind passage. However, it is clearly stated that this was a slag passage. It is clear that the furnace was worked with forced draught provided by bellows, since tuyères of a graphitic pottery were found. It will be noted

that the slag-passage is inclined on the down-hill side of the furnace so that the slag can run down the passage by gravity, a feature which Weiershausen states that he has frequently noticed in furnaces belonging to the Middle Ages. The Lölling furnace appears to be undated. A furnace of somewhat similar design was found at Hüttenberg in Austria (Weiershausen 1939, pp. 159-61, Abb. 43). The Hüttenberg II furnace goes back to Roman times, and it may even possibly be earlier. This type of shaft furnace was frequently used in the Middle Ages and indeed according to Weiershausen similar furnaces were still in use by the Löllingen peasants for primitive smelting as late as the nineteenth century. The furnace was of relatively large size, standing up to 6 feet in height, clay-lined, with stone retaining walls. After the smelting operation, the bloom was removed through an aperture in the side of the shaft, the hole being luted with clay when smelting was in progress. Sometimes, at least, forced draught by means of bellows was employed. Some points about this furnace remain confused. For instance, there is no information given as to the means adopted to tap the slag from the furnace.

At the Eisenberg, Pfalz, south Germany, were found rich remains of iron smelting dating to the Roman period. Part of a small shaft furnace (Eisenberg, No. 2) was found. A useful reconstruction of this is given by Weiershausen (1939, pp. 81-82). Such furnaces (Fig. 10, after Weiershausen, Abb. 17) are probably typical of the smaller free-standing iron-smelting furnaces of the Late Iron Age, or early Roman period. The hearth is dished, and a slag passage leads away from its rim. At a slightly higher level a hole is provided through which artificial draught may be provided by a bellows. The shaft and hearth are lined in the usual manner.

Although used for copper smelting, we must mention a most important discovery of an Etruscan shaft furnace. The discovery was made by an engineer, Lorenzo del Mancino, in 1934 near the church of Fucinaia (Witter 1942a).¹ Fortunately, enough of the furnace was preserved to enable a very valuable reconstruction to be made (Figs. 11-13 after Witter, Abb. 7-9). The brick-lined furnace shaft which formed the smelting chamber was 1.80 m. internal diameter at its base. This shaft was separated from a lower chamber, or ashpit, by a floor in which there were two rows of holes, 5 to 7 cm. in diameter. This dividing floor was supported by a central pillar, and access to the ashpit was by a large passage as shown in Fig. 13 (Witter, Abb. 9). The charge of fuel and ore will have occupied the shaft in the usual manner. There must also have

¹ See also *Studi Etruschi*, xi, 1937, pp. 305-41, and figs. 3, 4, 5, 7.

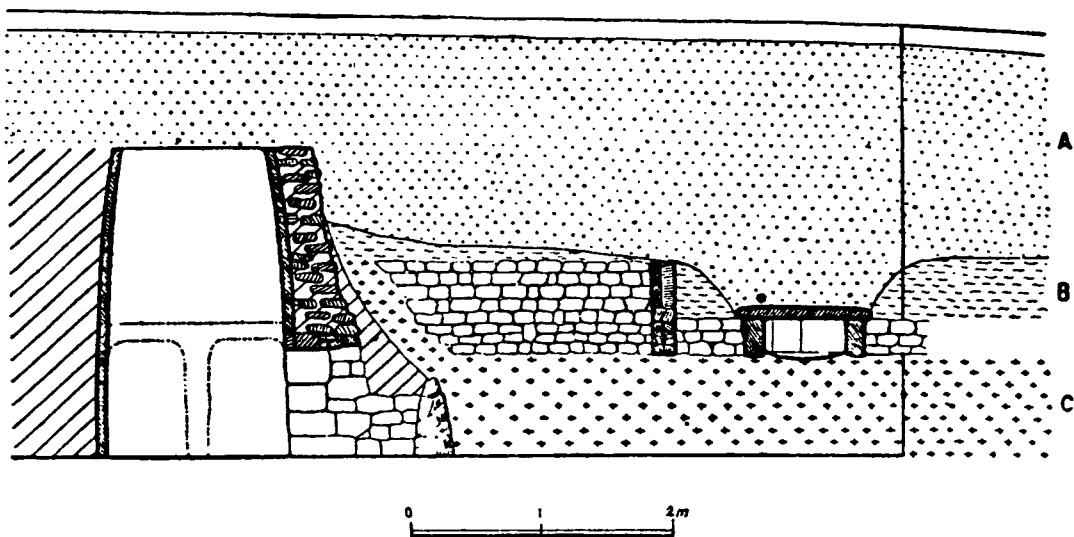


FIG. 11.

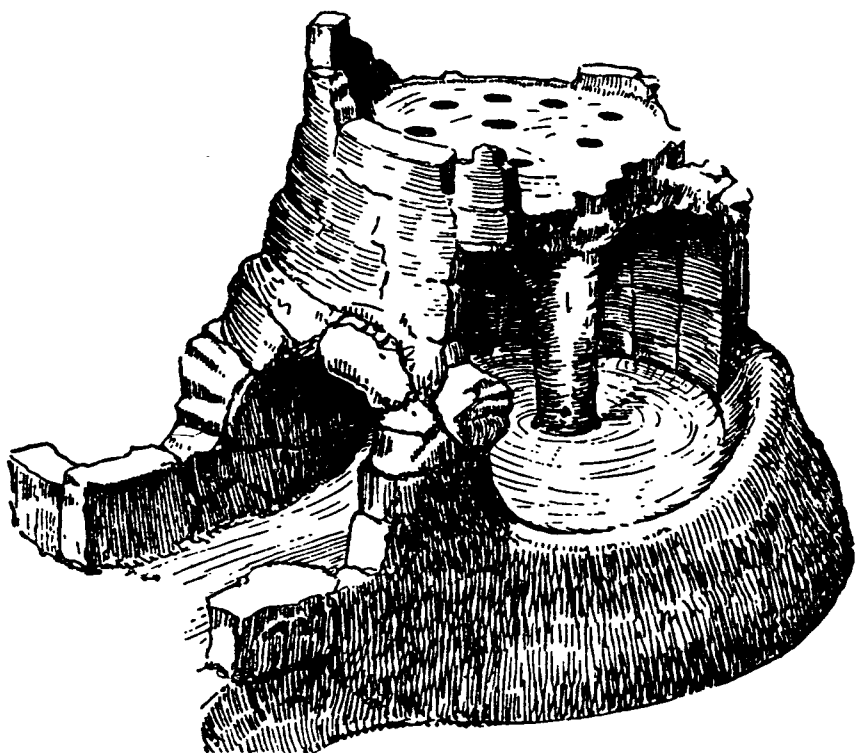


FIG. 13.

FIGS. 11-13. Etruscan shaft furnaces discovered by Lorenzo del Mancino (Witter 1942a, Abb. 7-9)

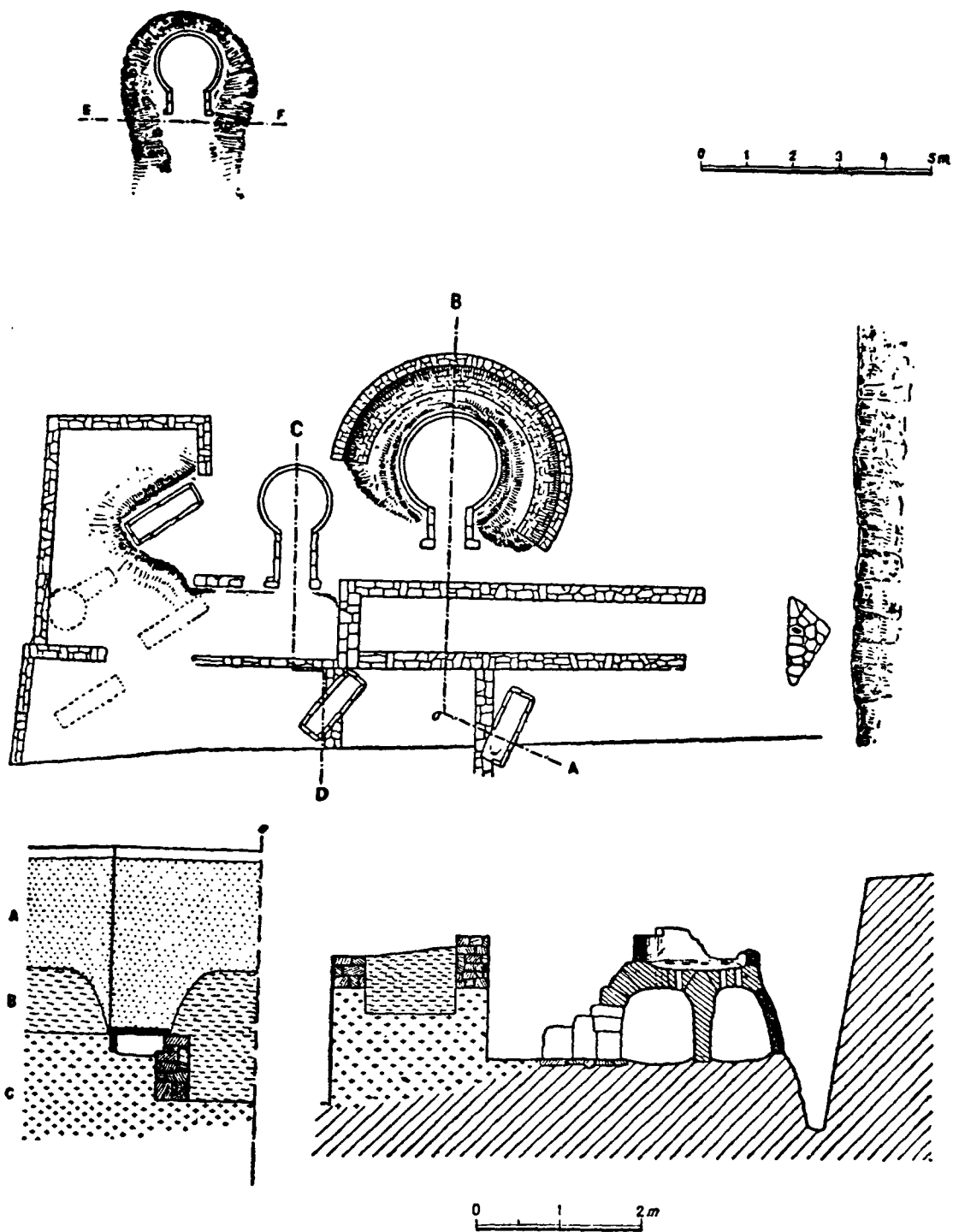


FIG. 12.

been some passage in the shaft for the purpose of tapping slag when the furnace was in operation. No such passage was found, but it may have been above that part of the shaft which was recovered intact. Natural draught was used, and the air supply would have been by way of the lower chamber, or ashpit, and then through the perforated floor to the shaft. The similarity in construction with the early Near Eastern pottery kilns is most remarkable. A furnace with domed roof and central supporting pillar was found at Arpachiyah in level TT8, while early pottery kilns with an ashpit and perforated dividing floor were found at Tepe Sialk and Khafaje (Coghlan 1942, pp. 27-29, Fig. 3).

VARIOUS FURNACES

There are a number of iron furnaces for which it would be unwise to attempt a classification because in some cases only the ground plan has been recovered, and sometimes the excavator's reconstruction cannot be regarded as reliable. Beck's well-known reconstruction of the Dreimühl-enborn furnace, near Saalburg, west Germany, can only be relied upon in respect of the hearth and slag passage which were actually found by excavation. The reconstruction of the upper portion of the furnace is hypothetical; it is also possible that the furnace may belong to the Middle Ages, although Beck considered it to belong to the Roman period. The Epernay furnace in France has been illustrated in the past as an iron furnace. This furnace, which was built into the side of a hill, had one opening at the bottom and another of much the same size at the top. Such an arrangement would provide no effective draught and, whatever the purpose of the furnace, it seems clear that it would not serve for the smelting of iron ore.

A well-known series of furnaces which form a distinct type, and may well be of early origin, is the Catalan furnace (Fig. 14 after Newton Friend, and also Forbes, 1950, Fig. 81A). The Catalan type is a pit furnace with an air blast introduced about half-way up the smelting cavity. The original distribution of the type was in Catalonia, and in the Ariège in France. According to Forbes (1950, p. 390), these furnaces were still in use in northern Spain in the provinces of Navarra and Guizpuzcoa in the seventeenth century A.D.; however, in origin the type is unquestionably far more ancient. Another ancient furnace, although possibly not dating before the Middle Ages in Europe, is the Osmund furnace (Fig. 15 after Forbes, 1950, Fig. 81C). As the figure shows, this furnace is of unusual design. Its distribution is a northern one, Finland, Sweden,

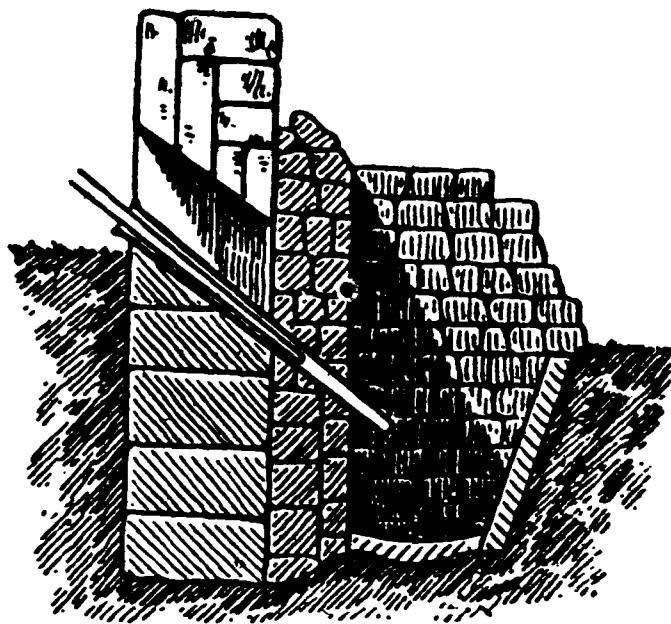


FIG. 14. The Catalan furnace (after Newton Friend, Forbes 1950, Fig. 81A).

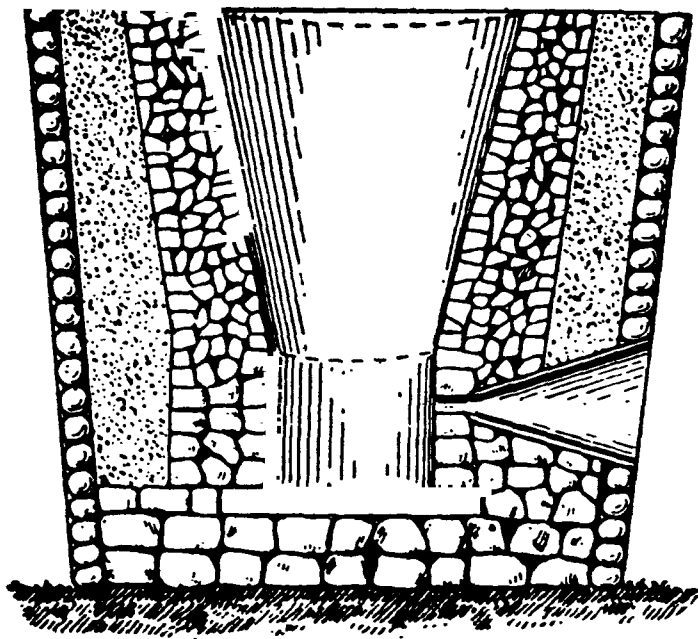


FIG. 15. The Osmund furnace (after Newton Friend, Forbes 1950, Fig. 81C).

and Norway. We mention it here because it may have led to the idea of the Stückofen (Fig. 16, Forbes 1950, Fig. 82). The Stückofen although late in date is a very important type, and in Professor Forbes's view these bloomery furnaces were worked in Carniola, Carinthia, Styria, Hungary, &c. The furnace may be described as two Osmund furnaces, one inverted over the other. In size they were up to 16 feet in height, and in

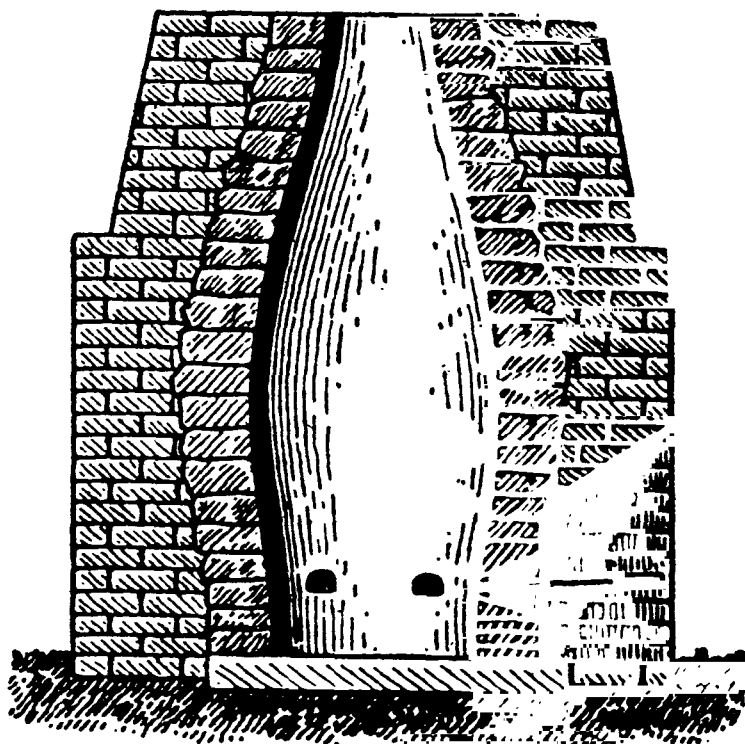


FIG. 16. The Stückofen (after Newton Friend, Forbes 1950, Fig. 82).

the large sizes forced draught was furnished by means of bellows worked by water power. No doubt the Stückofen was the prototype of our modern blast furnaces, for it is clear that although the normal function of the furnace was the production of a Stück, or bloom of iron, the construction and height of shaft combined with a powerful air blast would at times render the accidental production of cast iron likely.

Concerning the furnaces used in Britain, it is unlikely that the shaft furnace was used until the Roman period, and then perhaps only in the less backward provinces. Again, it is interesting to remark that the Romans do not appear to have invented water-driven hammers, or bel-

lows worked by means of water power. Under these conditions it follows that the size of bloom which it was possible to work was limited by the power of the sledge hammer. In a great measure this accounts for the early practice of forging or welding together a number of blooms when large and heavy pieces of iron were required. Under the Romans it is certain that the iron industry greatly expanded in quantity and quality, but they do not seem greatly to have advanced the technique of the iron furnace. Records and dimensions of Romano-British furnaces may be found in May's works to which we have already referred. Harold Dudley (1949, pp. 191 ff.) has recently given particulars of furnace and smelting sites in north-west Lincolnshire, and to various other authorities we have already given references.

Concerning primitive furnaces and iron smelting, a point of interest is the means adopted for the removal of the bloom and disposal of the slag. Here the evidence, when available, is often far from satisfactory. With small bowl furnaces the smelting process would not have been continuous, so that the furnace would have been extinguished, or, when of the contracted neck variety, even broken up, after the completion of each smelt. In such cases removal of the slag and iron of course would present no difficulty. With shaft and large domed furnaces the technique must have been different. In some cases liquid slag will have left the furnace through the wind passage, and as technique improved separate passages would have been arranged for the better control and tapping of the slag. As we have seen, it appears that in some of the larger furnaces the bloom was also removed through the wind passage. This cannot have been an easy or satisfactory method, and further evidence to throw light on this point is needed. A matter which we must remember is that the slag from pre-historic smelting must often have been far from liquid. Often it must have occurred when a suitable flux was not used that the slag would hardly liquefy, and would therefore remain in the furnace, from which it had to be removed when smelting was over. In some large furnaces this operation could have been carried out without much difficulty, but in some cases it would appear that a part of the furnace wall would have had to be broken away.

CRUCIBLES

There is evidence to indicate that the crucible process was connected with relatively early iron working, and Oliver Davies (1935, p. 58) points out that at Rudic crucibles with six tuyères were found. So far as I can

discover there is no evidence from the West to show that actual crucible smelting was practised; the crucible process was always confined to the conversion of wrought iron into steel by cementation. In a closed crucible containing charcoal and sometimes other substances, small pieces of iron would be converted into steel, as in the well-known crucible processes of the East. However, the crucible process would give but a very small yield as a result of considerable labour. Probably it was only applied at a relatively late period when material of specially high quality was desired. Carburization in a separate refining furnace was of course one method of partial conversion to steel, but it was also possible to obtain a semi-steel from the normal iron-smelting furnace, especially if the furnace was pre-heated so that higher than normal temperatures were attained. A suitable ore (such as brown ironstone) would have been necessary, and more charcoal than usual would have to be included in the charge. Accurate control of the air-draught would also have been necessary in order to reduce the oxidizing effect of the air entering the smelting zone of the furnace.

FUEL

In eastern and southern parts of the Old World fuel for the smelting furnaces must often have been rather a problem. To a very great extent the quality of the fuel determines the temperature which can be attained in the metallurgical furnace, therefore the smelting and melting processes were dependent to a considerable degree upon the availability of a good and suitable fuel. There is no doubt that, for general metallurgical purposes, charcoal was the fuel ordinarily employed, although ordinary wood (not converted to charcoal) may have been used too. Forbes (1950, p. 105) states that samples of charcoal have been found in early dynastic tombs at Naga el-Deir, and in a first-dynasty tomb at Saqqarah. Many kinds of wood, birch, oak, hazel, beech, &c., may be burnt for charcoal, but for good charcoal a close-grained wood containing the sap gives the best results. Mimosa, acacia, and tamarisk woods make good hot fires which may attain some 800 to 850° C. even without the application of an air blast. The normal process of charcoal burning by slow combustion in large heaps is well known, and can have varied but little from ancient to recent times. For those interested in the subject, a good account of the method of charcoal burning is given in Straker's book *Wealden Iron*, in the chapter which treats of fuel.

We know that charcoal was used from prehistoric times right through

to the seventeenth century, but it is rather remarkable to note how late its limited use as a fuel for smelting continued. In Great Britain the production of charcoal pig-iron from A.D. 1800 was solely in the hands of the Furness Ironmasters (Lord, 1945-7, p. 163), and in 1839 David Mushet noted that the making of charcoal pig-iron in Lancashire did not exceed 800 tons per annum. Again, in 1873 Hunt reported that the Newland furnace was operating with hot blast and a fuel mixture of four-fifths charcoal and one-fifth coke. In these cases, the limiting factor was the difficulty in obtaining the necessary charcoal in the large quantity required. Of even later date is the well-known Swedish charcoal iron which was produced in appreciable quantity (using birch wood for the charcoal fuel) certainly up to the outbreak of the Second World War.

Mineral coal is not a suitable metallurgical fuel owing to the fact that it contains harmful impurities, especially sulphur. It was not until the late seventeenth and early eighteenth centuries A.D., when it was discovered how to coke the coal and so to obtain a fine hard fuel free from noxious substances, that coal became the ideal fuel for the smelting of iron ore. Concerning the use of coal as a metallurgical fuel, some remarks by M. Jean Chevalier (1947-8, 1948-9, p. 60) are of interest. He states:

Ever since Simon Sturtevant had suggested, in 1611, the substitution of pit coal for charcoal for the reduction of iron ore in the blast furnace, metallurgists, when endeavouring to work the process, had always come up against the impossibility of preventing the coal from caking when burning in contact with the ore. The mass of hot material formed a bridge or scaffold across the furnace, preventing the descent of the charge above and also causing the iron previously reduced to be 'burnt' by the blast.

It is, however, quite certain that coal was used by the Romans for domestic purposes, for there is evidence of finds of coal in the remains of Romano-British villas. It would also appear that the use of coal for metallurgical purposes was not unknown to the Romans. Small fragments of mineral coal found in association with iron slag at Tiddington indicated to May that coal was used for smelting in Roman times; he also found satisfactory evidence of the use of mineral coal on thirteen different sites (Fieldhouse, May, Wellstood, 1931, p. 15; May, 1904, p. 76). At Tiddington the cast iron found was considered to have been melted with coal from an impure ore. At Warrington both cannel coal and charcoal were in use, the cannel coal for the ore-roasting furnaces, and possibly for the actual smelting, while charcoal was used in the

refining hearths. As we have said, coal is not a satisfactory fuel for smelting or refining, and its use by the Romans for such purposes must have been extremely limited. The results were no doubt unsatisfactory, but it is important to note that some use was made of coal so long before the discovery of coking. At Velem St. Veit, Austria, a brown coal (lignite), was in early use to some extent.

Chapter VI

THE TOOLS OF THE IRON-SMITH

THE iron-smith is concerned with forging, that is, the transformation of the metal into different shapes. Forging may be done in various ways, for instance, by beating out with hammers or special tools, by drawing down or jumping-up the metal, and by bending. Also, the welding process is frequently employed in the course of forging. The normal forging of iron is carried out at a good red heat, while in the welding process a higher temperature, known as a welding or white heat, is used. Forging of iron is quite a different technique from that of copper and must be carefully distinguished from it. In general, the basic difference between the two techniques is that copper and bronze are practically always worked in the cold state, and with the aid of frequent anneals. On the other hand, for all practical purposes iron must be worked at a red, or even higher, temperature. To a very limited extent iron and mild steel may be forged cold; the closing of a cold steel rivet is a well-known example of cold forging. However, for general forging cold working is not practicable. Apart from the harder nature of the material, any considerable hammering would cause most irons to start cracking, and iron cannot be annealed to return it to its original soft condition with the same ease as copper (we may note that iron and steel may be 'normalized', but this is a delicate process and would not have had application in early times). Hence, it is a general rule that iron and steel are always forged in a heated condition, and it is therefore clear that a fundamental difference between the iron- and copper-smith's work is that, as the copper-smith forges with his metal in the cold state he does not necessarily require holding tongs, while the iron-smith should possess efficient tongs to hold his red-hot iron firmly while it is being worked on the anvil. But efficient hinged tongs must have taken time to develop and the first iron-smiths no doubt had to work without them.

Modern primitive cultures show us that decidedly simple, and indeed primitive, tools have been in use by native smiths even up to the present day. In an interesting article Dr. Jeffreys (1952, No. 75) gives some notes on the methods of the Bikom (British Cameroons) blacksmiths. These smiths use very simple tools. A granite block serves for the anvil, and

heavy granite hammers of about 35 lb. and 22 lb. are used to expel the slag and convert the smelted bloom to a pig, then roughly to shape the pig to the article required. The final shaping of the forging is done with granite hammers weighing about 15 lb. and 8 lb. respectively. It is important to note that all these stone hammers are simply unhafted pounders, merely held in one or both hands. For finer work iron hammers are used. In the course of the smelting operation Dr. Jeffreys says that the bloom was held with wooden tweezers or tongs which, although they had been soaked in water, burst into flames. Further evidence of iron working with stone hammers among the Tula of Northern Nigeria is given by William Fagg (1952, No. 76). Here, the forging was conducted with stone and iron hammers. Mr. Fagg remarks, 'The special advantages of the stone hammer would appear to lie in its great weight and mass, concentrated along a narrow line, and also no doubt in its low conductivity of heat.' A stone anvil was also used by the Tula smith. Highly interesting was the use of a hollowed stone mould or matrix into which the hot iron was beaten with a heavy stone hammer so as to give it the desired form for the hoe being forged. As Mr. Fagg points out, we have here much the same technique as used with our modern drop forging and pressing machines, a modern repetition method which one would hardly associate with stone hammers and anvils! For the Southern Sudan, Garland and Bannister (1927, p. 107) give evidence for the use by native smiths of stone anvils, stone hammers, and green sticks which serve as primitive tongs. In the Pitt Rivers Museum, Oxford, there are many examples of such tools. In particular, there is a good example of blacksmith's bamboo tongs, 10½ in. long, from the Konyak of Tobu Village, Naga Hills, Assam (Coghlan 1951, fig. 14).

What may be termed the basic tools of the jobbing blacksmith, even at the present time, are not numerous or complex. Before considering early tools, it is useful to mention the major tools as used by a modern smith, but care must be taken to avoid the error of working backwards from modern tools. However, the student should be acquainted with the basic equipment of a modern jobbing blacksmith, and there are marked points of similarity between certain tools, ancient and modern.

(i) *The Forge*

A small blacksmith's forge with its bellows is still a very simple apparatus. The most elementary form in present-day use is the small portable or rivet forge, merely consisting of a circular iron tray on a stand which con-

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tains the coke and objects to be heated. Underneath the tray is a hand- or foot-operated bellows which supplies air to a dry tuyère, fixed in the side of the tray, for the provision of air-blast. The bellows of a small country

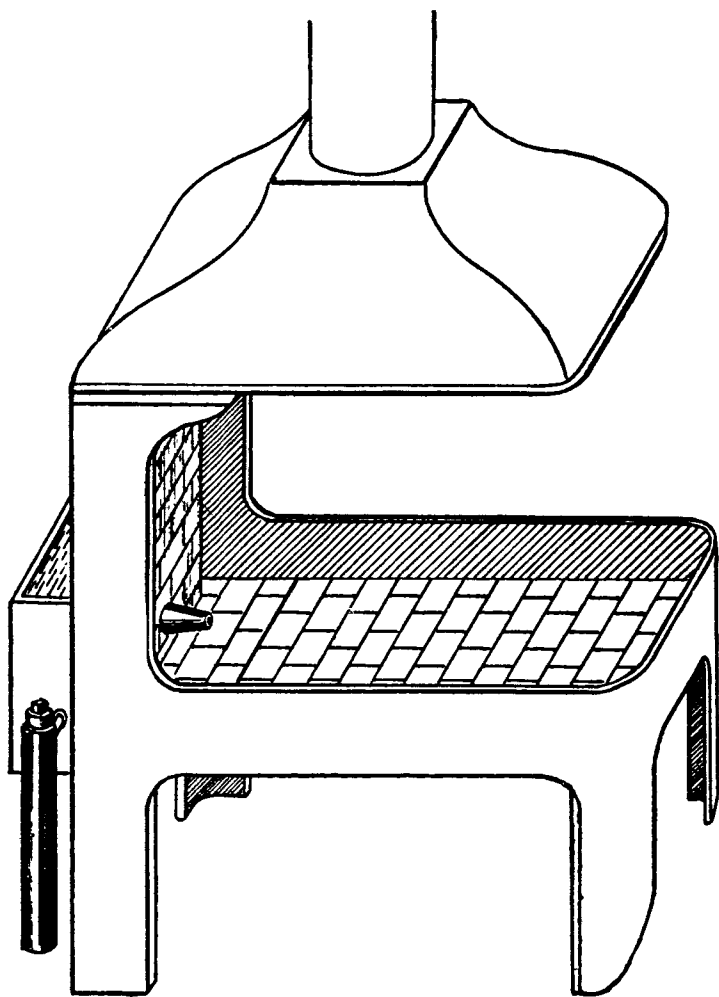


FIG. 17. Blacksmith's forge of cast-iron with water-cooled tuyère (Lillico 1949, Pl. 1).
Average size, 4 ft. sq. and 8 ft. high.

forge may still be worked by hand, but an advance over a really primitive forge is that the tuyère, or blast nozzle, is now practically always water-cooled. Also a brick or iron hood is now provided over the hearth to carry off the smoke and fumes from the fire (Fig. 17, after Lillico 1949, Pl. 1).

(ii) *The Anvil*

A substantial anvil with horn, or bick-iron, is an essential part of the smith's equipment. The top or working face of the anvil is usually provided with one or more holes for the reception of auxiliary tools. The modern anvil is much heavier than its early prototype. An average anvil of wrought iron weighs up to some 3 cwt., and has a hard-steel working

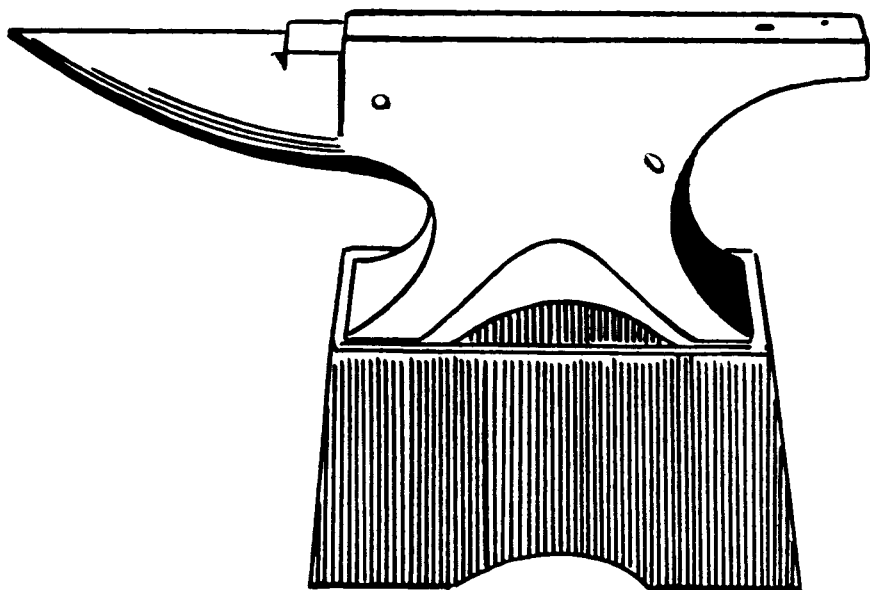


FIG. 18. Blacksmith's anvil, set on cast-iron mounting block (Lillico 1949, Pl. 8, Fig. 2).
Average weight, 2-3 cwt.

face welded to the wrought-iron body (Fig. 18, after Lillico 1949, Pl. 8, Fig. 2).

(iii) *Hammers*

In type these may be divided into sledge and hand, the sledge being, of course, a two-handed hammer. Modern smiths use sledges weighing from 6 lb. to 14 lb. A number of hand hammers are required to suit various jobs. As a rule these do not exceed $1\frac{1}{2}$ lb. to 2 lb. in weight. In this country the hand hammer is generally of the ball pene variety. When he is forging a square or rectangular section, the modern smith frequently uses a set-hammer. This tool is hafted and struck with a heavy hammer or sledge. Set-hammers are of two kinds, round- and square-edged. The round-edged hammer is used when working up to a radius, or fillet, on

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the piece being forged, while the square-edged set is useful when a sharp corner, rather than a radius, is required. See Fig. 19 (Lillico 1949, Pl. 13, Figs. 10, 11).

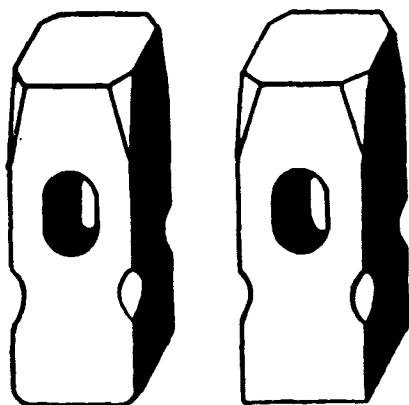


FIG. 19. Set-hammers, round- and-square-edged.
'As their name signifies, they set forgings' (Lillico
1949, Pl. 13, Figs. 10, 11).
Average, 6 in. high; weight, 5 lb. or more

(iv) *Tongs*

The smith must be provided with a good range of tongs in various sizes. Hinged flat-jawed tongs are an essential, also pincer-like tongs for holding round stock. Again, there are numerous special tongs for specific work. Some of these are hollow-jawed and caliper-jawed tongs in various shapes and sizes (Fig. 20, after Lillico 1949, Pl. 10, Figs. 1, 2, 5; Pl. 11, Fig. 7).

(v) *Chisels*

The smith uses chisels with which to cut his material, either when hot upon the anvil, or in the cold condition. Blacksmith's hot and cold chisels, or sets, are stouter tools than the mechanic's cold chisel. Usually the body of the tool is from $1\frac{1}{4}$ in. to $1\frac{1}{2}$ in. square, and the chisel is hafted in the traditional manner by means of a twisted iron rod, or with a wooden shaft. The hot chisel has a finer edge than the cold chisel (Fig. 21, Blacksmith's cold chisels or sets, Lillico Pl. 13, Figs. 3-5; Blacksmith's hot chisels or sets, Lillico Pl. 13, Figs. 6, 7).

(vi) *Fullers and Swages*

It is of interest to mention these tools for they are now used by every blacksmith. Fullers are used for the first operation in drawing down stock

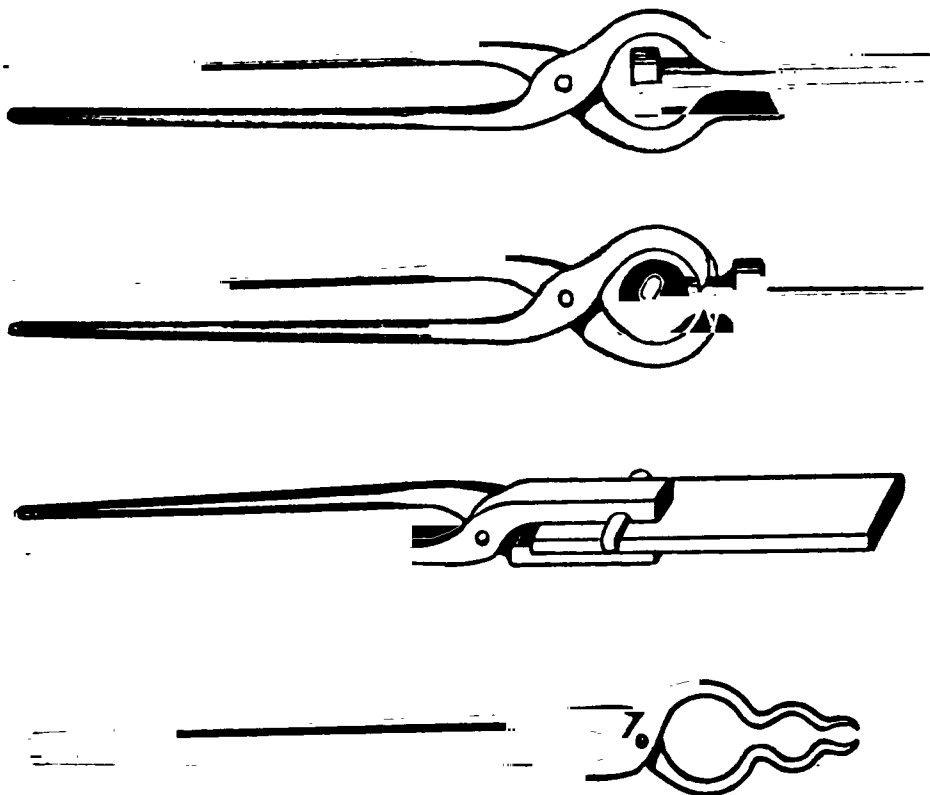


FIG. 20. Various blacksmith's tongs (Lillico 1949, Pl. 10, Figs. 1, 2, 5; Pl. 11, Fig. 7).
Usually 20-28 in. long; weight, *c.* 3-6 lb.

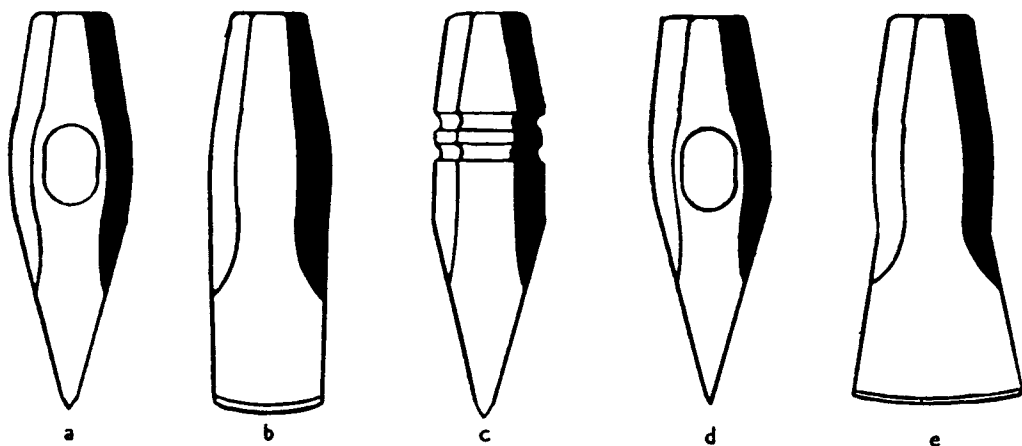


FIG. 21. (*a-c*). Blacksmith's cold chisels or sets. (*d-e*). Blacksmith's hot chisels or sets. (Lillico 1949, Pl. 13, Figs. 3-5; Pl. 13, Figs. 6-7.)
Average, 5-6 in. high; weight, 3-5 lb.

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and in forming recesses, fillets, and a great variety of bent and curved work. They are made 'top and bottom'. The bottom fuller rests upon the anvil, while the top fuller is a hafted tool and is struck in the usual way

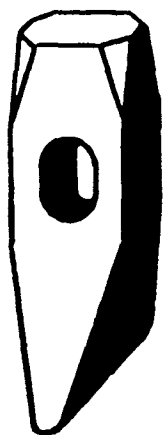


FIG. 22. Top fuller (Lillico 1949, Pl. 13, Fig. 14).
C. 4 in. high; 5 lb. or more.

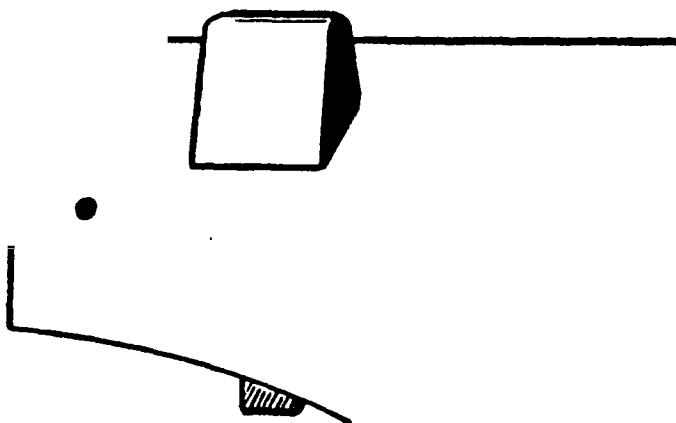


FIG. 23. Bottom fuller (Lillico 1949, Pl. 14, Fig. 3).

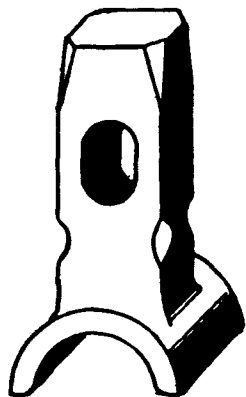


FIG. 24. Top swage (Lillico 1949, Pl. 13, Fig. 12).

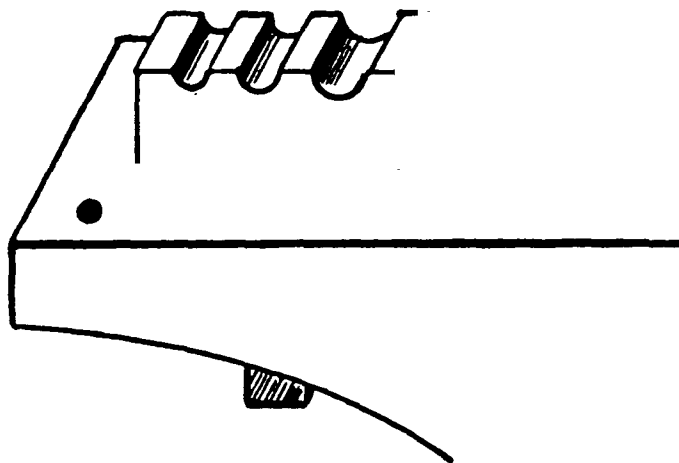


FIG. 25. Bottom or anvil swage (Lillico 1949, Pl. 14, Fig. 1).

with a hammer. In the same way, swages are 'top and bottom', and are used for working material into circular bars or rods. The bottom swage rests on the anvil, while the hafted top swage is held and guided by the smith whose assistant strikes the top swage down upon the work until a good and true bar has been forged. Fullers and swages were certainly

known by mediaeval times, but I do not know of evidence to prove a very early use. However, the idea of the swage is of very early origin, for the semicircular grooves cut in stone blocks, and in some bronze anvils, are in reality elementary bottom swages. See Figs. 22-25.

(vii) *Punches, Drifts, and Mandrels*

When iron is at forging heat it is relatively easy to pierce holes through it by punching. For instance, the shaft-hole in an iron hammer head may be made in this way. According to the shape of the hole which it is desired to pierce, the cross section of the punch may be square, rectangular, or oval. The method of punching will depend upon the size and shape of the hole, and also upon whether the metal is to be swelled-out round the hole. If it is not desired to swell-out the metal round the hole, a punch with a point but slightly smaller than the diameter of the shank is used. When the metal has to be swelled-out round the hole, as may be observed in many iron hammers of Roman date, a small hole is first punched through, and the metal is then opened out by the use of taper drifts. Mandrels are really long drifts, and form a convenient method of holding, and making solid, hollow forgings while they are being worked upon under a forging heat.

(viii) *Files and Saws*

These tools really belong to the mechanic who receives and finishes the smith's forging, but naturally the jobbing smith will have, and at times use, files and saws. The use and appearance of the modern file is too well known to call for any description here. A very large amount of the smith's cutting-off work is done with the hot or cold chisel on the anvil, but sometimes it is convenient to use a saw and therefore a large hacksaw is usually included in the tool kit.

Having given some slight idea of present-day smith's tools of a very simple nature, we may turn to the prehistoric and early historic material. Here, we at once encounter the difficulty that, owing to the nature of the material, iron tools are not very plentiful, and such material as there is has not received very detailed study. Indeed, the only serious works available to English students, and entirely devoted to prehistoric and early tools, would appear to be Petrie's *Tools and Weapons*, published in 1917; and more recently Ohlhaver's *Der germanische Schmied und sein Werkzeug*, Leipzig, 1939. A small but useful work is Professor Childe's *Story of Tools*, 1944. For the northern countries, Dr. Andreas Oldeberg's

important work, *Metalltechnik under Forhistorisk Tid*, Lund, 1943, should be consulted. Here, illustrations and description of many early tools will be found. It is to these works that we must turn for much of our information.

The prehistoric smith's hearth would have been of simple construction. A bellows with blast nozzle and a paved hearth with some stone walling to contain the fire and conserve heat would meet the requirements of an Iron Age smith. Concerning the anvil, we have seen that the stone anvil has been used to the present day, and it must certainly date back to the very beginning of any form of metal working.

Anvils

Bronze anvils are not a tool of the iron-smith. We may, however, mention that such anvils, while never common, are a well-known type in Bronze Age Europe. The most simple form of bronze anvil is hornless, and is merely a conical or wedge-shaped block. This variety appears to be decidedly rare. The horned bronze anvil is a much more numerous and advanced type with considerable variations. A most interesting small bronze anvil comes from Chalons-sur-Saône, France. It has two horns and two separate anvil-faces. According to which of the horns is used as a tang, a different anvil-face is presented to the work. The same principle is found in an anvil from a hoard at Bishopsland, Co. Kildare, Ireland (see Raftery, *Prehistoric Ireland*, Fig. 182). Small anvils of special type for making needles or pins are provided with half-round grooves for forging or finishing the work. We have here an idea which later developed into the swage. A good example of such an anvil is that from Fresnés la Mère, Calvados, France (Fig. 26, from the anvil in the Ashmolean Museum).

According to Ohlhaver (1939, p. 32), the following types of iron anvil are to be found in prehistoric and early historic times:

- (a) Anvils with one or two horns.
- (b) Hornless anvils of most varied size.
- (c) A small anvil for secondary work such as whetting scythe-blades by hammering, i.e. field or mower's anvils.
- (d) Nail-making anvils, and anvils for special purposes.

In the European Iron Age the horned anvil (a) appears to be very rare. This is peculiar, in view of the fact that the horned anvil was quite well known in the Late Bronze Age. Even the Roman cultures do not appear

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to have favoured the normal type of anvil with horn or bick-iron. At least for central and northern Europe this type does not become really important until around the sixth century A.D. Two of these late type

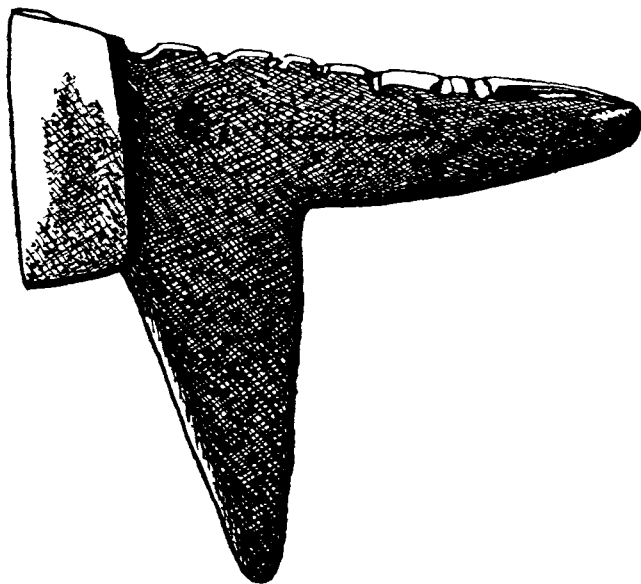


FIG. 26. Bronze anvil from Fresnés la Mère, Calvados, France, now in the Ashmolean Museum. Weight $10\frac{1}{2}$ oz. Scale 1/1.



FIG. 27. Iron anvil from Norway (Ohlhafer 1939, Taf. 31, 1).

anvils are shown in Figs. 27, 28 (after Ohlhafer Taf. 31, 1 and Taf. 26). Fig. 27 (Ohlhafer Taf. 31, 1) is a good type of a single-horned iron anvil from Norway. It will be noticed that it has a long and thin bick-iron, and

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in fact tends towards what is known as the L-shaped anvil, so called because such anvils resemble an inverted letter L. Fig. 28 (Ohlhaber Taf. 26), also from Norway, is of interest in showing a mediaeval iron anvil in which the horn, or bick-iron, comes off the top of the anvil body in the modern manner. It will be noted that both these anvils, although of relatively late date, are more or less tanged. That is, they do not stand



FIG. 28. Medieval iron anvil from Norway (Ohlhaber 1939, Taf. 26).

upon their own base like our modern anvils, but were secured by being driven into a heavy block of timber.

What Ohlhaber terms hornless anvils of varied size (*b*), are not of great interest. They are crude blocks of iron which have been used as anvils. Again, there are many smaller Provincial Roman anvils which are not always, except in size, clearly to be distinguished from small field, or mower's anvils. With the stake, field, or mower's anvil, we come to a large and important class. Such small anvils have been much used by country people for whetting, or work hardening by hammering, the blades of scythes, down to modern times. Indeed, they are probably still in use in some parts of Europe, for I have personally observed a small field anvil in use by a mower in France in the Dauphiné during 1936. They can

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also, of course, be used by a smith for any other suitably light work. Naturally, if used by a smith they would only serve for making very small and light forgings. For such field anvils Ohlhaver (1939, p. 35)

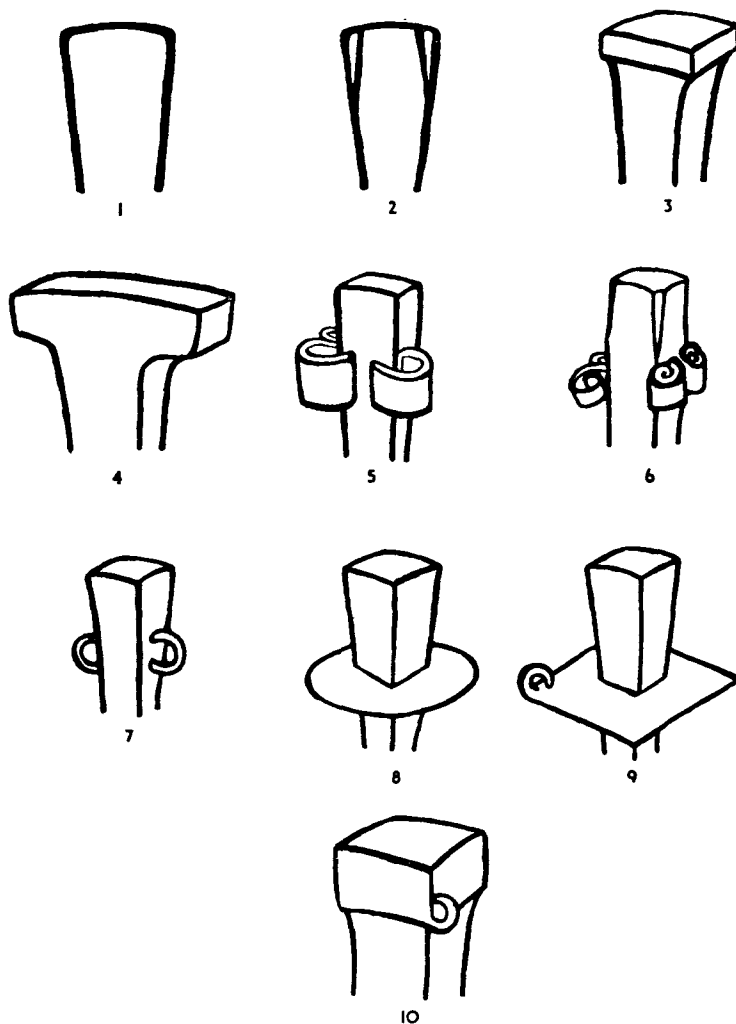


FIG. 29. Various field anvils of the Roman Period (Ohlhaver 1939, Abb. 10).

quotes an average length as between 15 and 25 cm., and a length of anvil face usually between 3 and 4 cm. In their most simple form these anvils are merely wedge-shaped pieces of iron of square or rectangular section (Fig. 29 after Ohlhaver, Abb. 10, various field anvils), as in Nos. 1 to 3. To act as a stop, the field anvil sometimes has a rectangular hole or slit through the body, through which are passed strips of iron, the ends of

the iron strips being curled into loops or spirals (Fig. 29, Nos. 5, 6). Special types are known in which instead of the anvil being pierced for strips, the function of a stop is performed by a square or circular plate through which the taper tang of the anvil passes, the stop plate wedging securely against the taper of the anvil tang (Fig. 29, Nos. 8, 9). Then there is the 'eyed' anvil which is suspiciously like a tent peg. However, at least in some instances it appears that the 'eyed' anvil is quite genuine (Fig. 29, No. 7). The anvils discussed above are of Roman date, and, so far as present records show, the true field anvil may be said to be Roman or later.

For nail-making, and large iron anvils, we must again turn to the Roman period. The Romans, and smiths working under Roman instruction, forged very substantial objects at times. Such work can be carried out on a heavy stone anvil, but a heavy iron one is better. These big anvils are often merely cubes of iron hollowed out underneath so as to give four feet which rest on the ground. In general, such big tools are hornless, but have an extension of the working table to one side, and a nail heading, or other device, at the opposite side (Fig. 30, Lindenschmit 1911, Taf. 46). Such anvils may be up to 30 cm. in height. They are not common, for Ohlhaber cites only five examples. The method used for making an iron nail, and the function of the nail-heading hole in the anvil, or of the separate nail iron, is shown in Fig. 31 (Ohlhaber 1939, Abb. 36). It will be seen that five operations are involved:

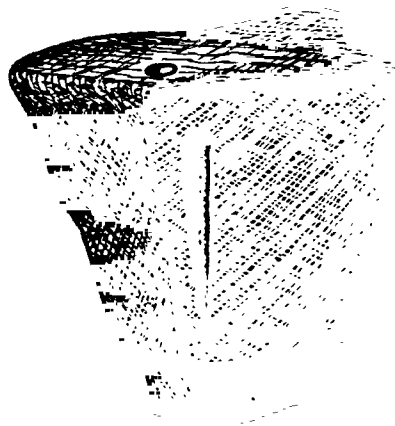


FIG. 30. Large Roman anvil, 21 cm. high, 18 cm. diameter, tapering to 8 cm. (Lindenschmit 1911, Taf. 46).

1. A round rod of iron, larger in diameter than the shank of the nail, is prepared.
2. The point of the nail is formed at the end of the rod.
3. The rod is drawn down on the anvil to the required diameter and length of the nail.
4. The rod is cut off, leaving enough metal from which to form the head.
5. The final operation is to forge the head, using the nail hole in the anvil, or a separate nail-iron as shown.

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To form a square nail the same method is adopted, but the shank of the nail is, of course, forged to a square section.

A point which will strike those with some practical knowledge of iron forging is that, with the exception of the large Roman anvils just mentioned, the anvil appears very small and light when compared with the hammer. At first iron was not so very plentiful and the stone anvil was in

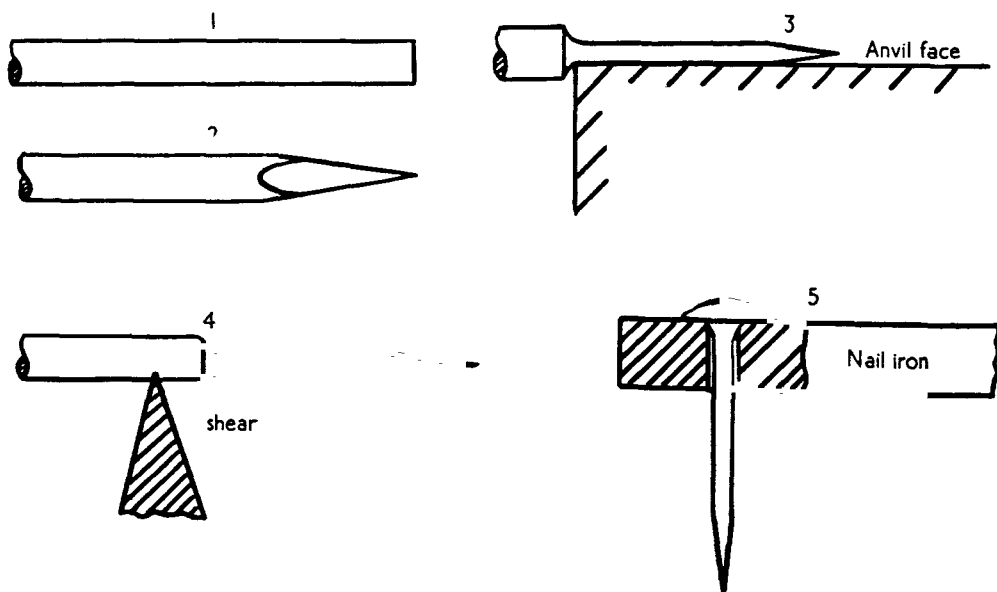


FIG. 31. Making an iron nail (Ohlhaber 1939, Abb. 36).

all probability much used. Here the smith would have plenty of weight at his disposal. Also, many qualities of stone would stand up to the stress of serious forging if a large homogeneous block was selected to serve for the anvil. In the mediaeval German anvils the dimensions remain surprisingly small. One would consider that most of the anvils recorded are for 'fine' work, rather than for that of the ordinary blacksmith.

Hammers

The hammer made of stone or wood is one of the oldest known tools and, of course, it long predates the discovery of iron. Stone hammers were used in the Palaeolithic and succeeding ages, and in many parts of the world the use of stone hammers continued down to recent times. In metal, we find the hammer well established in the Bronze Age. In western

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Europe the socketed bronze hammer was a popular tool, but it was not heavy, being suited to light work only. Indeed, many of the socketed bronze hammers must have been used for fine work only (Fig. 32, bronze

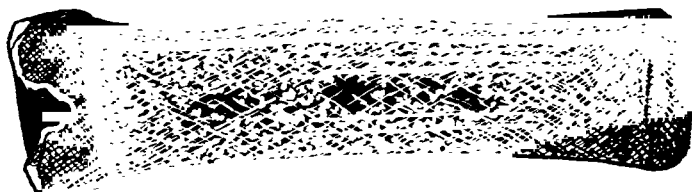


FIG. 32. Bronze socketed hammer from Fresnés la Mère, now in the Ashmolean Museum. Weight 4 oz., Scale 1/1.

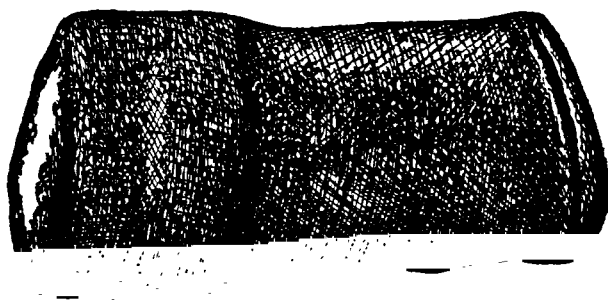
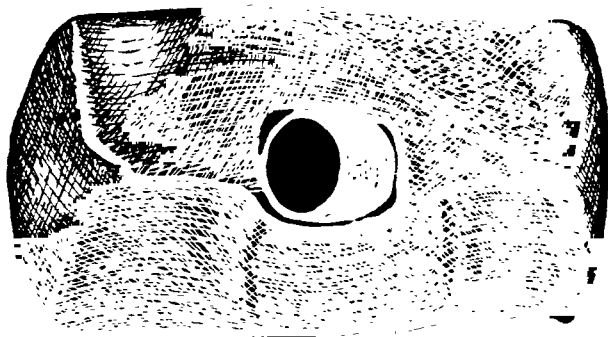


FIG. 33. Heavy bronze hammer from the Mitterberg, Austria. 15.7 cm. long, 7-8.5 cm. diameter, 4317 gr. weight (Pittioni 1951, Pl. IV, No. 2).

hammer from Fresnés la Mère, Ashmolean Museum). On the other hand, quite heavy bronze hammers with features in common with the modern sledge are known (Fig. 33, Bronze hammer from the Mitterberg,

Austria, Pittioni 1951; Pl. IV, No. 2). In general such bronze hammers predated the iron worker in Europe, and they are not a tool of the iron-smith, but with the coming of iron it was natural that the hammer should appear in this metal. However, iron hammers are not numerous before the Roman period, although various forms in iron do appear on the Continent in early La Tène times (Oldeberg 1943, ii, p. 11). There are two methods of making and shaping the hammer. First, a simple rectangular block is forged from which to make the tool. Through this block, where it is required that the shaft-hole shall be, a slit is cut out with the hot chisel; then the shaft-hole is completed by drifting through with round, oval, or rectangular drifts. After this operation the claw, when required, is drawn down. According to the size of the shaft-hole, the drifting operation expands the sides of the hammer around the hole, but it does not increase the thickness of the hammer when looked at in side view. Secondly, when it is not desired that the sides of the hammer should be swelled around the shaft-hole, the sides may be forged down using a mandrel in the hole, so that the shaft-hole retains its true shape during the forging. Naturally such forging will increase the depth of the hammer (when looked at in side view), around the shaft-hole. The difference between this method and the more modern technique in which the expansion of the metal is more or less avoided by the use of a blunt-ended punch will be noted. Various shapes of iron hammer heads are shown in Fig. 34 (after Ohlhaver, Abb. 14). Ohlhaver (1939, p. 43) considers that both the swelled shaft-hole and the parallel-sided forms of hammer are to be found in prehistoric contexts, and are certainly well established by the Roman period.

During Roman times the hammer assumed the form of some of our modern tools. The iron cross pene hand hammer was very similar to the mechanic's hand hammer as used in France and Germany today. It is interesting to note that the cross pene hammer with square-section body appears, even today, to be a continental type while the well-known ball pene mechanic's hand hammer seems to be a British development. As with the hand hammer, so the heavy iron sledge had taken quite a modern appearance under the Romans (Figs. 35, 36, Roman hand and sledge hammers, after Lindenschmit 1911, Taf. 46, Nos. 800, 799). We have mentioned that the modern smith uses a set-hammer, and it is interesting to observe that such tools go back to Roman times. One such is figured by Ohlhaver, from Dürna, Reidlingen, Württemberg (Fig. 37 after Ohlhaver, Abb. 48).

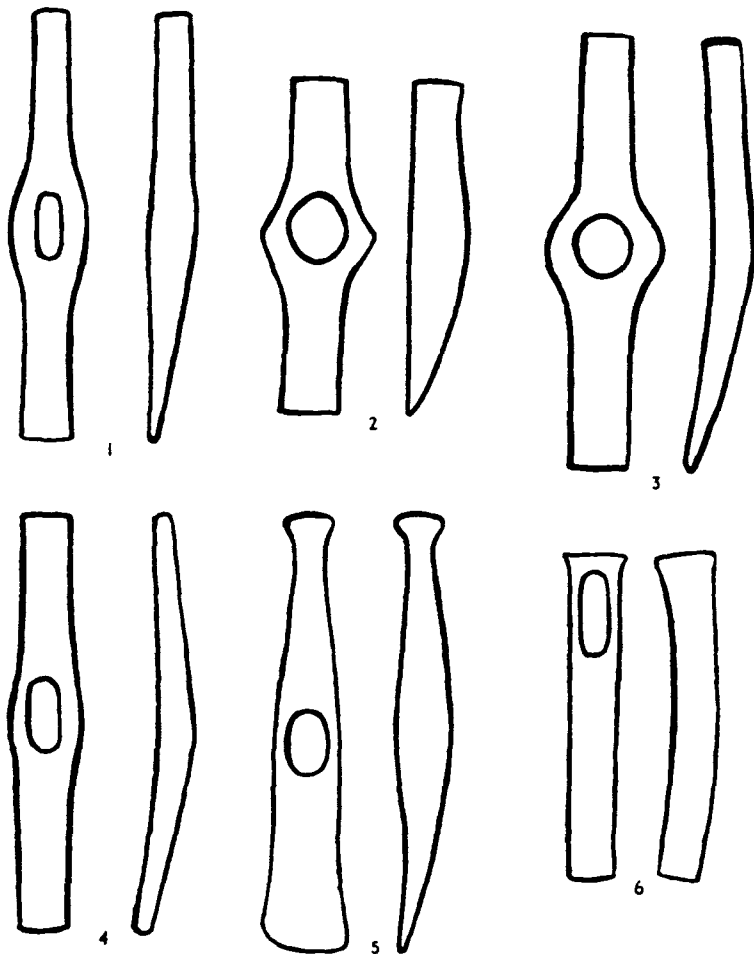


FIG. 34. Various shapes of iron hammer-heads (Ohlhaver 1939, Abb. 14).



FIG. 35. Roman hand-hammer 18.5 cm. long (Lindenschmit 1911, Taf. 46, No. 800).

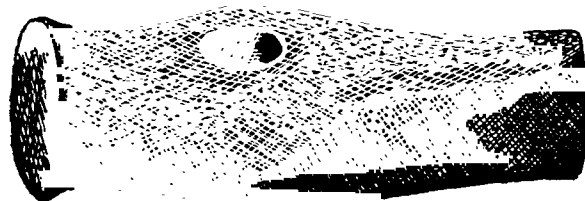


FIG. 36. Roman sledge-hammer, c. 20.3 cm. long, shaft-hole 3 cm. wide (Lindenschmit 1911, Taf. 46, No. 799).



FIG. 37. Roman set-hammer from Durnau, Reidlingen, Württemberg (Ohlhaver 1939, Abb. 48).

Tongs

The earliest metal tongs used were no doubt of the simple spring-back variety, or, in other words, they were merely enlarged tweezers. Simple tweezers made from one piece of metal are of very early origin, for copper tweezers were found in the tomb of Semerket, one of the last kings of the first Egyptian dynasty. Again, the tweezers enlarged to form a spring-back tongs of considerable size are depicted in a drawing of Egyptian bronze-workers from the tomb of Hapu, of the date of Thutmosis IV, 1420-1411 B.C. (Coghlan 1951, p. 79 and Fig. 10). Tongs of such early date would have been made of copper or bronze and, while perfectly suitable for removing small crucibles or light objects from the fire, their value to the iron-smith, who needs a firm grip when forging his iron, may well be questioned. However, we must remember that the simple spring-back tongs has served as part of the smith's equipment to mediaeval times, and for other uses until today. Such tongs have been used until recently in the forging of springs and chain-links. They have the advantage of a constant grip, and are therefore comfortable and convenient for the smith to hold. Undoubtedly when provided with a slip-ring to increase the holding power the iron spring-back tongs is a useful tool.

Among modern primitive iron-workers a green withy frequently served as tongs, and there is no reason why, where suitable withies or other timber were available, they should not have been used by the prehistoric smith. More or less to hold, and at any rate to guide, a rough furnace bloom while it was being hammered upon a stone anvil to expel charcoal and included slag in the process of consolidating the iron would be within the capacity of withy tongs. For such use we have ample evidence from modern primitive smiths in Africa. For the actual forging of implements the withy tongs would be at a disadvantage owing to their low holding power and tendency to catch fire, but they could be used for the forging of simple objects such as spears, knives, and hoes, in which it would not be necessary to bring the whole of the metal up to a forging heat at the same time, or when a projection could be left on the object which would serve as a cooler portion to be gripped by the wooden tongs. For example, the Bikom blacksmiths (Jeffreys 1952, No. 75) used withy tongs or tweezers when shingling their iron bloom upon a stone anvil, and a form of wooden handle to enable the iron blank to be manipulated on the anvil when forging. The frequency with which spring tongs occur in the Middle Ages in Europe would lead one to suppose that they may have been more frequent in Roman and Iron Age times than the known

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finds indicate. Ohlhaver (1939, p. 67) mentions a spring tongs of 20 cm. in length from the Hallstatt cemetery, and also an example from Býčiskála which may be of the same period. Of Provincial Roman finds,

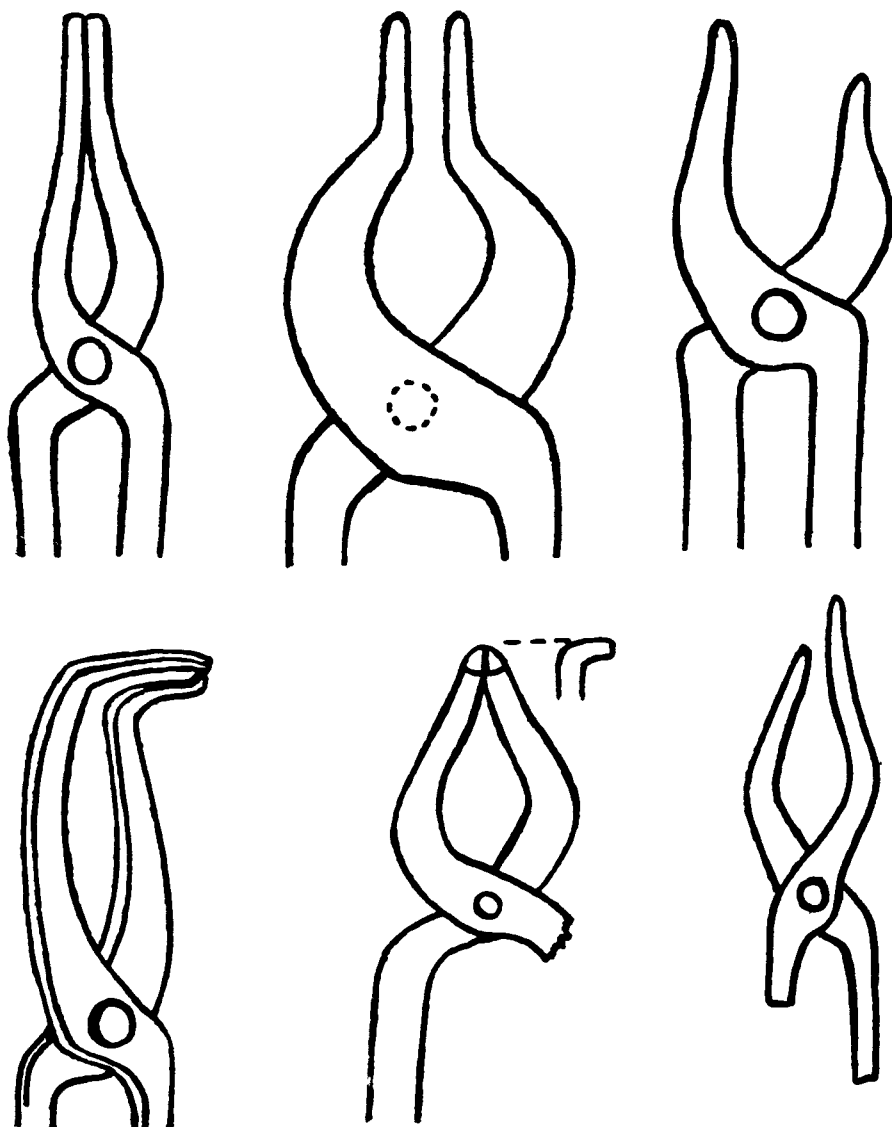


FIG. 38. Various tongs (Ohlhaver 1939, Abb. 24).

there is one from France. From 'German' finds, Ohlhaver gives but three examples.

The solution to the problem of an efficient tongs was, of course, the

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invention of the hinged variety, and it is significant that in general this form appears with the coming of iron. Hinged tongs are certainly exceedingly rare, if indeed present, before the Iron Age in Greece when we find the modern form depicted upon an Attic vase which shows a Greek smithy of about 500 B.C., but Evans (1921, i, Fig. 70) does show an

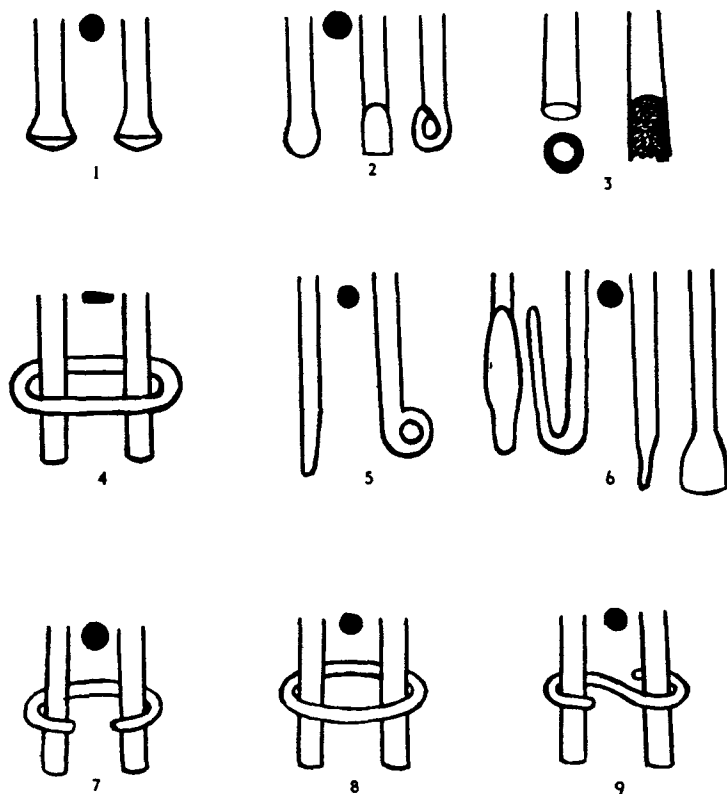


FIG. 39. Various tong-handles and methods of locking them (Ohlhaber 1939, Abb. 29).

example as early as Minoan II from Mochlos. From late in the Iron Age, and commonly in Roman times, large and well-designed hinged tongs are found. Fig. 38 (after Ohlhaber, Abb. 24) illustrates some types of jaw. It will be observed that the smith has advanced to the stage at which he forms a variety of jaws to suit the work in hand. Indeed, we may say that the Roman smith had a number of the shaped jaws which we use today. Again, some of the Roman tools exhibit the same means for locking the tongs upon the work which we still employ. Rings, hooks, S-clips, &c., were used to lock the handles (Fig. 39 after Ohlhaber, Abb.

29). Except for some special shapes, and better material, it may be said that with the heavy Roman hinged tongs 'terminal' development had been attained.

The Chisel

Of the many prehistoric chisels, it would be very difficult to separate those belonging to the iron-smith. However, we may say that only a semi-steel, or steel-tipped chisel would be of service to the smith. The small

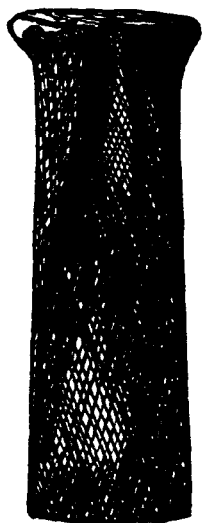


FIG. 40. Bronze Age flat chisel, scale 1/1 (Pitt Rivers Museum, P.R. 1473).

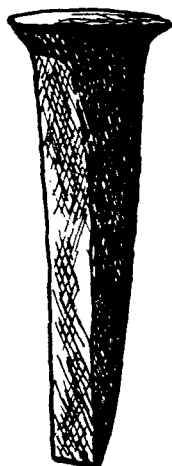


FIG. 41. Roman flat chisel 11.5 cm. long (Lindenschmit 1911, Taf. 46, No. 798).



FIG. 42. Roman cross-cut chisel 10.3 cm. long (Lindenschmit 1911, Taf. 46, No. 814).

and light line and punching chisels much used for decorative work do not concern us. Since the iron-smith's chisel must be able to stand up to direct and heavy blows on its shank, it follows that we may exclude socketed chisels, and chisels which have long slender shanks. Also, chisels with widely splayed blades do not belong to the forge. The smith's chisel has changed but little in the course of the centuries. The modern tool is tapered down to the cutting edge at an angle varying between 15 and 30 degrees, while the cutting edge itself forms an angle of some 45 to 70 degrees. Such proportions may be observed in the early iron chisels, at least from Roman times onwards. The cutting edge of the chisel is, of course, hardened, while the butt and shank are left in a soft condition. As today, cross-cut and flat chisels are known (Figs. 40-42). Recent and

modern hot chisels are often hafted by means of an iron rod with a loop passing round the shank of the tool under its butt. This method of holding the chisel is necessary when large forgings at red heat are being cut upon the anvil. The work of the Iron Age smith would have been of a lighter nature, and he would no doubt have been able to hold his chisel with the tongs, or even in the hand.

Fullers and Swages

To the blacksmith, top and bottom fullers are most useful tools. However, I cannot find any evidence for their use in prehistoric or Roman times. It seems likely that these tools would be known to the more skilled Roman smiths, but unless evidence to prove their early use is forthcoming, we cannot consider them to be earlier than the mediaeval period. We have already mentioned that the swage must be of early origin, and that its prototype may be found in the semicircular grooves cut in some Bronze Age anvils. Evidence for the swage is extremely scanty, although Beck (1892, ii, Abb. 121, and p. 539) has recorded some Roman examples. Ohlhaber (1939, Taf. 16, and p. 2) illustrates an excellent bottom swage which is provided with a spigot for use as an auxiliary tool socketed into the top of an anvil. However, this tool is of mediaeval date and it seems probable that the swage only became popular at some time during that period.

Punches, Drifts, and Mandrels

Punches, drifts,¹ and mandrels² are the most simple of tools, and must have been used by the smith even in Iron Age times. They are so simple that no description is necessary. The punch, particularly when used upon cold sheet metal, requires to be adequately hardened.

Files

The file is a very important tool, and would have been used by the smith for smoothing and finishing his forgings. In the Bronze Age bronze files are known, but these would have been valueless for iron working and were what we should now term rasps, today being mainly used for wood-working. Files first become of value for cutting the harder metals with the introduction of iron, when we begin to find files of rectangular, square, and round cross-sections. Before it was discovered

¹ Tools for enlarging or shaping holes in metal.

² Rods round which metal is forged or shaped.

how to carburize the iron so that a reasonable temper could be imparted to it, the file was an inefficient tool although it would have had its value for cutting the softer metals. Also, a bad file was better than no file, for the traditional grinding process was slow and laborious. Apart from the metal used, the efficiency of a file depends upon the number and method of cutting the teeth. In general, for cutting the harder metals it pays to use a fairly fine file, that is, one with a large number of teeth. For wood, and very soft metals like lead and tin, a rasp-like file with a much coarser tooth is employed. As we have mentioned elsewhere (Coghlan 1951, p. 86), there are various ways in which the teeth of a file may be formed. Modern files are made with the teeth arranged as single or double cut. With the single-cut file there is but one series of teeth which are cut at an angle across the working face of the tool. For filing harder metals, double-cut files are more suitable. Here a second series of teeth is cut at the same angle, but crossing the first series. Hence, a large number of triangular cutting points are left standing up in contrast to the continuous cutting edges of a single-cut file. Cutting the teeth at an angle across the working face of the file is a method which renders the tool smoother in operation and more efficient. It would appear that the teeth of early files were cut with a chisel before the hardening was carried out.

Dr. Oldeberg (1943, ii, p. 104) remarks that in a considerable number of prehistoric files, especially in the Scandinavian area, the cut was usually perpendicular to the longitudinal axis of the file, and square over the whole width of the surface, while in other cases the teeth were obliquely inclined across the face. Possibly even before Roman times the double-cut system of the modern file may have been known. It certainly seems that the late Iron Age toolsmith had grasped the true principle of the file.

The hardness and temper of an iron file is, of course, a vital factor in the efficiency of the tool. Here, we unfortunately have very little information to go upon because hardly any early files have been examined by metallurgists. However, two files from Steinsburg, Römhild, Kr. Hildburghausen, Thuringia, Germany, have been examined by Hanemann (1921-2, pp. 95 ff.) He investigated a large and a small file, not later in date than Roman. Both were found to be made of an iron which had been converted into steel which was capable of being hardened. As in modern practice, the working part of the file had been hardened, while the tangs were left soft. Hanemann puts forward a theory as to how the file blanks were prepared, but this aspect is of more interest to the metallurgist. We may say that the investigation showed that the smith must have had

practical knowledge of how to carburize his iron up to the point at which hardening becomes possible, and, moreover, understood correctly the appropriate method for hardening his material. This agrees with Carpenter and Robertson's research which we have mentioned on page 59, where it is noted that carburizing, quenching, and tempering were practised by A.D. 200.

Concerning the antiquity of the file, Dr. Oldeberg¹ would consider that iron files appear at least during the sixth century in Assyria, while in Egypt an iron file was included in a workshop find at Thebes. This find is considered to be connected with the invasion of the Assyrians in Egypt in the year 663 B.C. During the La Tène period iron files are to be found in the south of Europe, and in the Roman period they become common. In Europe, the list of recorded files is a short one. For instance, for La Tène, and the early Roman period, Ohlhaver only gives particulars of finds from the La Tène settlement at Neuchâtel, Steinsburg in Thuringia, Stradoniss in Bohemia, Ronsden in west Prussia, and Neuguth, west Prussia; Petrie (1917, p. 44) mentions a 'crippled' file from the Auvergne, France, and a good one from Silchester (Evans 1894, pp. 139 ff.). He also states that the fine-cut file begins with the Assyrian group, where the rasp is also found in a perfect form, exactly of modern shape and detail.

Saws

The saw is a tool of great antiquity, for as long ago as the Magdalenian period in the south of France serrated flint blades were used as saws for cutting small objects of wood and bone. In the Ancient East, the metal saw is early, and in Egypt it appears to date back to the First Dynasty (Petrie 1917, p. 43). These first saws would have been of copper, later followed by those of bronze and iron. We do not know when the saw, as distinct from the bronze, and possibly iron saws used for wood cutting, became a part of the smith's equipment. Once it was learned how to temper a chisel so as to make a file, and to temper the file so that the teeth of the saw could be cut, technical difficulties had largely been overcome. Hence, there is no reason why an iron saw should not have been carburized and tempered so as to render it capable of cutting wrought iron during the late Iron Age in Europe. It is certainly significant that, from a large hoard of iron tools of the Roman period from the Heidenburg bei Kreimbach, north of Kaiserslautern, Rhenish Bavaria (Lindenschmit

¹ Private communication (also Coghlan 1951, pp. 86-87).

1911, Taf. 46), we find an iron saw with correctly raked teeth set in a metal frame (Fig. 43). This tool appears to be a prototype of our modern metal-worker's hacksaw, and should be quite capable of cutting wrought

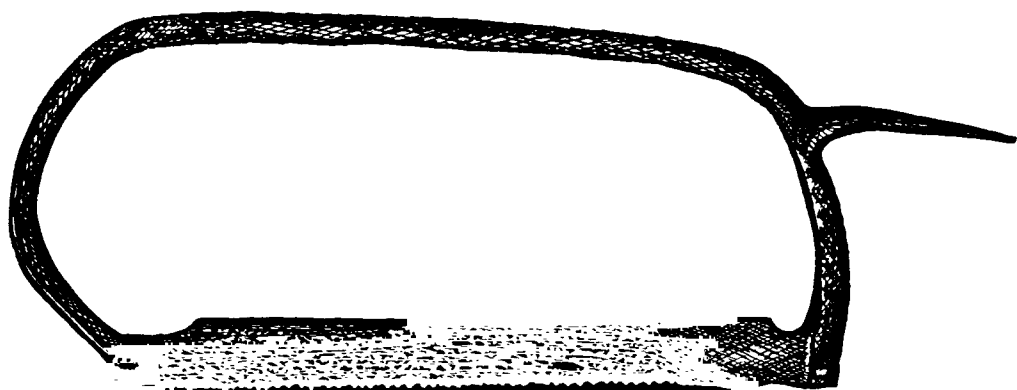


FIG. 43. Roman saw of iron in metal frame (Lindenschmit 1911, Taf. 46, No. 805).

iron. A very similar tool is also figured by Oldeberg (1943, ii, p. 104, Fig. 210), but here the blade is no less than 1 cm. in thickness, and Oldeberg refers to the tool as an arc-file. Hence, it is not quite clear whether we should consider the Swedish tool as a hacksaw with an unusually wide blade, or as a frame-mounted file. At least, it is clear that we may ascribe a saw, comparable to our metal-cutting hacksaws, to the Roman, if not to an earlier, period in Europe.

Chapter VII

THE TECHNICAL ART OF THE SMITH TO ABOUT A.D. 1000

To conclude these notes it is of interest to examine, in so far as the evidence available permits, the progress made by the smith in his art up to about A.D. 1000, by which time a high standard had been attained. Indeed, after A.D. 1000 there was probably no very revolutionary progress in the smith's art until the seventeenth or eighteenth centuries when the turning lathe, and other machinery, created the need for yet further development in tools and material. Again, we do not attempt to discuss art in iron-working in the generally accepted sense of the term because examples of artistic iron work of the La Tène, and other periods, will readily be found in archaeological textbooks.

The primary advance in the smith's art was to refine and improve the quality of his iron. If we except the use of iron as a semi-precious metal with small application to decoration and ornament, the bulk of the early iron produced was for the manufacture of tools and weapons. Primitive bloomery iron is not sufficiently hard to give the fine cutting-edge so necessary in a good tool or weapon; hence the first step in the evolution for which we must seek is some method of hardening the iron. This could be attained by carburizing. With primitive methods the penetration of the carburized 'case' would be slight, most likely adequate for a thin and slender object like a small knife, but not sufficient to be satisfactory for a substantial chisel or axe. For these heavier objects there was a method to overcome the difficulty—the piled or compacted structure. If a number of thin laminations of iron were separately carburized, and then piled and forge-welded together, the forging so obtained would have a reasonable diffusion of carbon throughout its mass. In this way the iron may be brought into the range of the steels, which may then be further hardened by heat treatment. As we shall see, this ingenious technique was actually developed in the prehistoric period. Such smith's work was far from primitive, indeed it may be called decidedly skilled. The technique still has a limited application in the manufacture of some special steels.

So far little attention appears to have been directed to the evolution

of the smith's art in early times and the evidence available has many gaps, leaving much to be desired. The best pre-war scientific research, at least by British workers, of which I am aware is that by Carpenter and Robertson in 1930 (pp. 417-54). In an endeavour to give some outline of the subject we shall make use of their investigations, together with much new research kindly carried out for the Pitt Rivers Museum by Mr. T. H. Williams and Mr. P. Whitaker of Messrs. Stewarts and Lloyds, arranged through the good offices of the British Iron and Steel Research Association. Of the specimens examined by Carpenter and Robertson, it is to be noted that the earlier examples, although found in Egypt, may well be imports because the Iron Age was of relatively late occurrence in Egypt.

We have the following specimens to consider:

EGYPTIAN KNIFE. *Period, c. 1200 B.C.*

Report. Carpenter and Robertson, 1930. Specimen no. 2.

This small knife was made by welding two pieces of metal together, the line of the weld extending along the whole length of the specimen to the point. The two pieces of metal had been brought to approximately the same composition by carburizing. The knife had been air-cooled, producing small specks of ferrite and fine pearlite, and the authors report that it was carburized so as to make the carbon content at the cutting-edge about 0.8 per cent., falling to about 0.6 per cent. in other parts. Brinell figures showed that the hardness varied between 269 and 302. These are high figures for unquenched steel, and it is interesting to compare them with the low figures obtained from a Roman sickle in which the material had been quenched but spoilt in an attempt to temper it.

EGYPTIAN KNIFE. *Period, c. 1200 B.C.*

Report. Carpenter and Robertson, 1930. Specimen no. 3.

The carbon gradient from the edge to the back of this specimen showed that it had been carburized. How the carburizing had been carried out is a matter of surmise, but after cooling, the metal was again heated into the critical range and then air-cooled. For technical reasons, the authors suggest that the carburizing process was not carried out by placing the knife in a charcoal fire, but by some other means that necessitated slow cooling, for instance packing in a crucible with charcoal and other instruments. Hardness at the edge of the knife near the hilt varied between 285 and 269 Brinell, and at the point between 255 and 269. At the back, the hardness varied between 179 and 197 Brinell.

EGYPTIAN AXE. *Period, c. 900 B.C.*

Report. Carpenter and Robertson, 1930. Specimen no. 8.

A variable structure was revealed in this axe. The carbon content is also variable, and in certain positions rises to around 0.25 to 0.3 per cent. The iron had been carburized and the authors conclude that the axe was finally heat-treated by quenching the cutting-edge. If water was the medium used for quenching, it would appear that only the cutting-edge was immersed. The Brinell hardness was also variable. At the edge the hardness is 207, rising to 229 a little higher up the point, and falling to 116 as the body of the tool was approached.

EGYPTIAN AXE. *Period, c. 900 B.C.*

Report. Carpenter and Robertson, 1930. Specimen no. 9.

As a result of carburizing, the carbon content of this axe decreased from about 0.9 per cent. at the cutting-edge to a very small amount at about 1 in. from the edge. The cutting-edge was quenched in water, and it is important to note the authors' statement that on withdrawing from the water the main part of the axe was still at a red heat, and conduction of heat from the body reheated and tempered the edge. It would be interesting could we know if this self-tempering was accidental, or intentionally sought for by the smith. Most likely it was intentional. The result was most successful, for the hardness figures increase from 62 Brinell in the ferrite of the body to 363, 388, and finally to the very considerable hardness of 444 Brinell at the cutting-edge.

EGYPTIAN HOE. *Period, c. 800 B.C.*

Report. Carpenter and Robertson, 1930. Specimen no. 7.

This hoe was simply forged from bloomery iron and had received no subsequent heat treatment. It is of interest in showing how variations in composition of the separate particles of the direct iron, and variations in the forging conditions, render a wide range in hardness in the same tool. For instance, near the tip where the ferrite grains were large the Brinell hardness was 116. Higher up the tool where the ferrite grains were smaller, the hardness was 137. Again, in an area where the structure was small-grained and contained some pearlite, the hardness varied between 149 and 187. In another area where the ferrite grains were large and the pearlite small, the hardness was 163.

TRIPOD. *Assyria, Nimrud. Period, late 8th century B.C.*

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate I, Fig. 2, and pp. 180, 202.

This specimen has been completely converted to iron hydroxide. No metallic portion was left, so that analysis was impossible. Examination of a section would indicate that it was made from piled wrought iron. This is valuable information as it indicates that the compacting technique was known at least as early as the late eighth century B.C.

EGYPTIAN CHISEL. *Period, c. 700 B.C.*

Report. Carpenter and Robertson, 1930. Specimen no. 6.

The investigation showed that, after forging to shape, this chisel underwent the following processes:

- (a) It was carburized at the point.
- (b) It was then heated at the point.
- (c) It was finally quenched by immersing the point only.

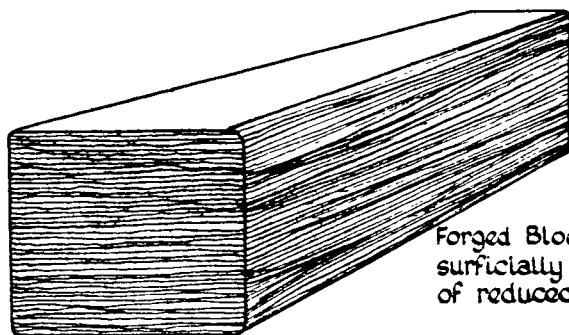
According to the position in the chisel blade the carbon content varied from very low to about 0.4 per cent. Also, the hardness varied according to position from 137 to 302 Brinell. The maximum hardness was not attained at the cutting-edge itself owing to the fact that the material near the cutting-edge had to some extent been decarburized and particles of ferrite were fairly plentiful. It is clear that this tool was made by a skilled smith, as shown by the technique of heat treating and quenching at the point while leaving the body of the chisel unhardened as we frequently do today. Obviously the smith well knew what he was about, although it may be noted that he did not know of, or perhaps it is more likely that he did not wish to risk experimenting with, any further tempering operations after he had quenched the material.

SPEAR. *Syria, Deve Hüyük. Period, 600–500 B.C.*

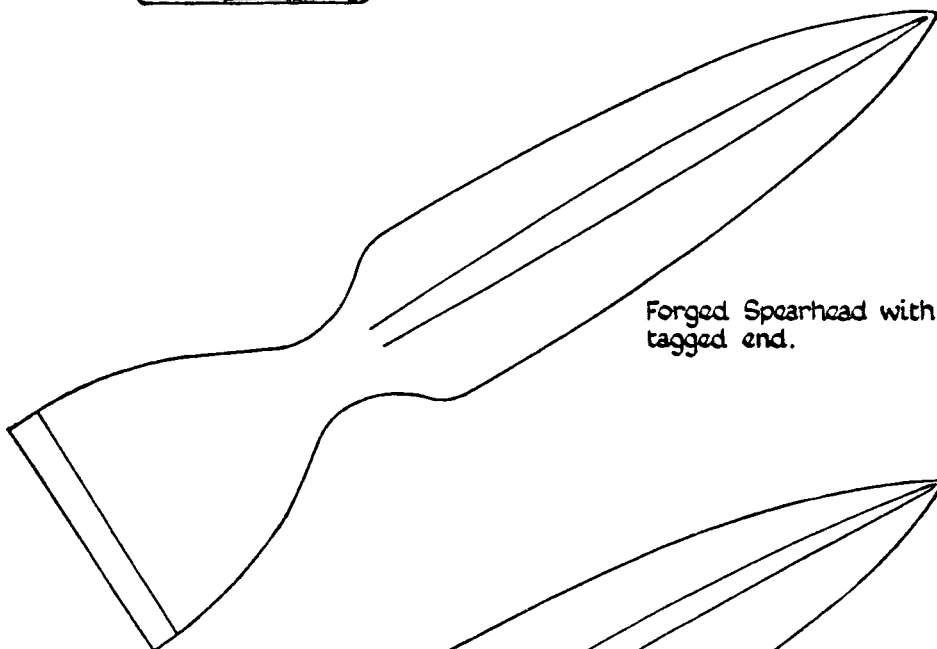
Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plates II–IV, and pp. 180, 202.

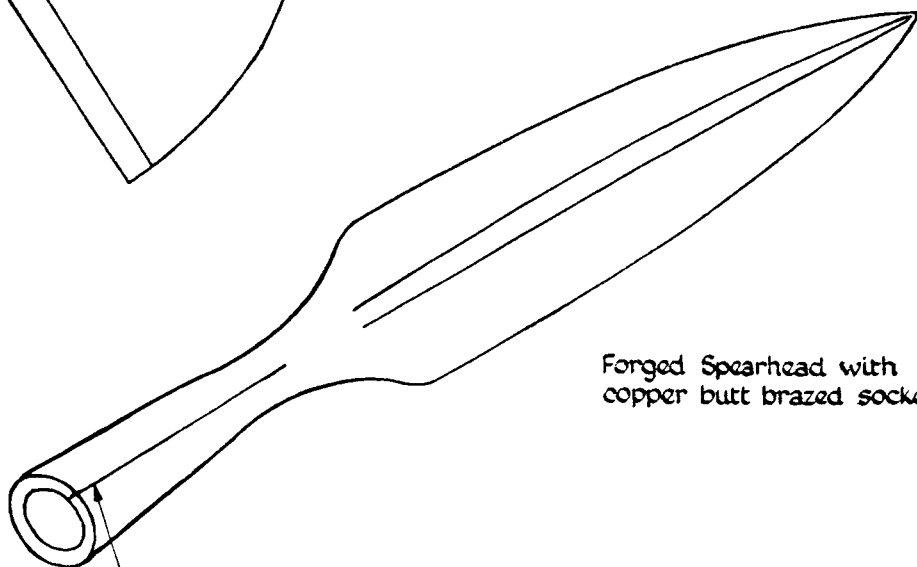
The material of this spear is forged carburized steel made from reduced sponge iron. Average carbon content is 0.18 per cent., but in places as high as 0.6 per cent. The high nickel content of 0.32 per cent. is unusual. The spear has been forged from about fifty plates or layers of sponge iron piled into a block (Fig. 44, from the Report of Messrs. Stewarts and



Forged Block built up of many superficially carburised layers of reduced sponge iron.



Forged Spearhead with tagged end.



Forged Spearhead with copper butt brazed socket

Copper butt
brazed joint

FIG. 44. Forging a socketed spear-head, 600-500 B.C., Deve Hüyük, Syria (from the Report by Messrs. Stewarts and Lloyds).

Lloyds). The majority of the plates have been surface-carburized during heating for forging, the compacted structure resulting in a highly developed water-marked pattern somewhat similar to damascene steel blades produced from cast steel. A noteworthy feature is that the tubular taper socket, which was forged from a 'tagged' end, has been brazed and forged together with impure copper. Hardness ranged from 108 Vickers in the low carbon zones to 153 Vickers in the higher carbon bands. There is no indication of hardening and tempering. A high degree of skill is shown in welding and forging. No doubt the smith could have hardened the spear had he wished. The hardness figures quoted are typical of a modern mild steel, the strength of which would be quite satisfactory for a mid-rib spear of such proportions.

SPEAR. *Yugoslavia, Vače. Period, 5th century B.C.*

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plates VI-VII, and pp. 184, 203.

The report states that this spearhead has been forged from wrought iron with a very variable carbon content of from less than 0.1 to exceeding 0.6 per cent. locally. The hardness varies from 103 to 134 Vickers. The spear was made by rolling over a faggot of wrought iron to form a forge welded tubular section. The tubular section was completely collapsed at one end to form the point, but still retains its taper tubular form at the socket portion. The point of the spear is unhardened.

EGYPTIAN KNIFE. ? *Europe. Period, c. 300 B.C.*

Report. Carpenter and Robertson, 1930. Specimen no. 4.

This small knife had been carburized but not quenched. The hardness of the small-grained structure in the middle of the knife varied between 137 and 143 Brinell; that of the remainder varied between 95 and 107. For its period, this seems a poor specimen and without features of any particular interest.

IRON PICK. *Palestine, Lachish. Period, Iron Age, before 588 B.C.*

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate V, Fig. 1, and pp. 182, 202.

This early specimen was made from a very pure base wrought iron which had been carburized prior to piling and forging. Production from a pure haematite or magnetite ore is indicated. Determination of carbon

gave 0.196 per cent., with hardness varying from 136 to 183 Vickers. The report of Messrs. Stewarts and Lloyds indicates that the point of the pick was quenched from a very high temperature. It would therefore appear that the smith who made this pick was aware that, at least under certain conditions, an increase in hardness was to be obtained by quenching from high temperature.

IRON SWORD. *Höganäs i Skåne. Period, Probably Hallstatt D.*

Report. Dr. Andreas Oldeberg, 'Ett märkligt järnsvärd från Höganäs i Skåne', *Vänersborgs Museums Skriftserie* 4, Vänersborgs 1952, pp. 27-70.

Dr. Oldeberg thinks that this unusual iron sword came from the east Hallstatt region, or from even farther to the east. If that be so, the sword would belong to the Hallstatt D period, or to the transition to La Tène. The relatively high copper content of the blade shows that a copper-bearing iron ore was used as the source of the metal. Perhaps it was siderite, which is to be found in the east Alpine region. The analysis of the blade was:

Ti	V	Mn	Fe	Co	Ni	Cu	Sn	Pb	As
0.01-0.1	<0.01	0.1-1	<i>grund</i>	<0.01	<0.01	0.1-1	-	-	<0.01
			<i>massa</i>						

It will be observed that the iron contained an unusual amount of copper and manganese, approximately 0.1 to 1.0 per cent. in each case. The carbon content was variable, but was apparently about 0.5 per cent. The addition of manganese may be said to increase the strength and work-hardening properties of a steel (as in the modern low-carbon manganese steels with carbon of 0.2 to 0.3 per cent. and manganese 1.0 to 1.75 per cent.), while the addition of copper in the ranges up to 2.5 per cent. would presumably increase the yield point and impact value of the material. From Dr. Oldeberg's report it appears that the Höganäs sword was not quenched and tempered, nor was it work hardened after forging to any proved degree. Owing to the improved qualities of the copper-manganese blade, such post-forging was perhaps found to be unnecessary.

The construction of the sword hilt is of interest, and the assembly is of quite advanced design (Fig. 45 after Oldeberg's Fig. 7). First, there is a decorated socket which is seated on the blade. Next is a sheet-metal tubular hand-grip surrounding the tang; the longitudinal seam of this hand-grip has been brazed with a bronze alloy. Finally, the end of the

tang was riveted down upon a winged terminal, so securing the complete assembly. The composition of the brazing alloy is:

Ti	V	Mn	Fe	Co	Ni	Cu	Sn	Pb	As
<0.01	<0.01	0.01	1	<0.01	<0.01	<i>grund</i>	1-10	0-0.1	<0.01
		-0.1				<i>massa</i>			

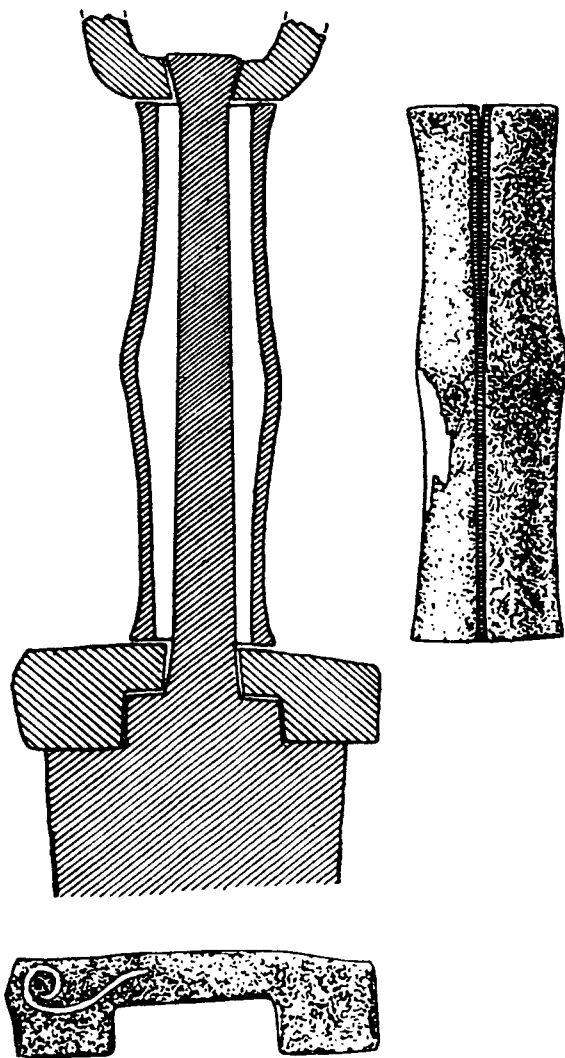


FIG. 45. Construction of the hilt of the Höganäs sword (Oldeberg 1952, Fig. 7).

It is clear that the swordsmith was highly skilled. He was able to forge the iron hand-grip to a series of graceful curves, and afterwards to braze the joint. Even today, the construction of the Höganäs hilt would rank

as quite a neat piece of smithing. During Hallstatt times the use of copper, or of a bronze alloy, in the brazing of iron must be relatively rare, although we have the use of copper for brazing the spear socket from Deve Hüyük (Cap. X, p. 181). It is remarkable that the technique of brazing bronze and iron was known and practised from very early times. This subject has been dealt with at length by Maryon (1949, pp. 108-12), who cites examples of early brazing, e.g. the Whittingham bronze sword of the late Bronze Age, and for iron, a ring of Roman workmanship from Uriconium, Wroxeter, Shropshire, dating from before A.D. 380, which had a welded joint and a second joint of which the brazing material was found to be copper. In a Hallstatt sword from northern Europe, Dr. Oldeberg (1943, ii, pl. xv, p. 215) finds evidence for the use of brazing with a silver alloy.

SAMPLE FROM AXE-EDGE. *No.* 22006.

Prähistorische Sammlung im Naturhistorischen Museum, Wien.

Loc. Magdalenenberg bei St. Marein, Jugoslavia, Tumulus II, Grave 1 and 2.

Period. Hallstatt, sixth century B.C.

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate V, Fig. 2, pp. 183, 202.

SAMPLE FROM LANCE-HEAD. *No.* 22016.

Prähistorische Sammlung im Naturhistorischen Museum, Wien.

Loc. Hallstatt, Gräberfeld, Grave 783.

Period. Hallstatt, sixth century B.C.

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate V, Fig. 3, pp. 183, 202.

The small sample taken from axe-edge No. 22006 was found to be of rather high-carbon wrought iron with numerous entrapped slag filaments. The hardness of the sample was 149 to 165 Vickers, and there was no sign of any attempt at hardening. The small sample from lance-head No. 22016 was of pure wrought iron with carbon of less than 0.04 per cent. Again, there were numerous entrapped slag filaments. The hardness of the sample was 145 to 154 Vickers, and there had been no attempt at hardening. Perhaps one would not expect much attention to hardening in a lance-head, but had the skill of the smith been at all high, one would expect some endeavour to be made to harden an axe. However, it will

be noticed that both specimens were untreated, and their hardness was approximately the same.

IRON SWORDS. *Italy, Esino and Bergamo. Period, La Tène.*

Report. Storti, C., and Mariani. E. 'Una spada gallica del III periodo di La Tène'. In *La metallurgia italiana, alti notizie*, no. 5, maggio 1953.

Doctors Storti and Mariani carried out a technical examination of two swords of iron belonging to the La Tène period. One was from the furnishing of one of three tombs at Esino Lario, and the other, from a private collection, came from the province of Bergamo. First, considering the Esino sword, it was found that in the core-metal of the blade there was an absolute prevalence of pearlite over ferrite. In the external areas ferrite tended to prevail. The material of which the Esino sword was made exhibits a steel structure with the surface layer definitely decarburized and with many inclusions, some of notable dimensions and generally elongated. In the authors' opinion, the billet from which the sword was forged consisted of a true steel, a steel with a noteworthy lack of homogeneity, but on the whole certainly approaching a pearlitic eutectoid steel with a carbon content averaging 0.7 to 0.8 per cent. The sword had not been subjected to any heat treatment or hardening (except hammer hardening of the cutting-edge), and exhibits a resistance comparable to that of a semi-hardened modern steel with a carbon content of about 0.5 to 0.6 per cent. with an ultimate tensile strength of 55-60 Kg. mm².

The metal of the Bergamo sword showed very different characteristics. As to slag, the material was exceptionally pure; in certain areas only were very small inclusions to be found. Here we are dealing with a soft and pure iron of formation similar to that of an Armco iron. Hardness determinations taken in certain typical areas showed that the ultimate tensile strength of the iron would not exceed about 32 to 33 Kg. mm². The Bergamo sword is of far less advanced technique than that of Esino. The material was very soft and could not be hardened or tempered. It would make an exceedingly poor sword for it could not be hardened, and although it would not break, it would bend with great ease. It is a good example of the 'soft iron sword' of textbooks, and far removed from Déchelette's (1914, pp. 1116 and 1129) view that La Tène swords were of highly advanced technique.

TWO IRON SWORDS. *Switzerland. Period, La Tène, c. 50 B.C.*

Report. Stewarts and Lloyds for Pitt Rivers Museum.

Plates VIII–X, and pp. 185–6, 203.

Through the kindness of the Director, Professor Dr. Alfred Bühler of the Museum für Völkerkunde, Basel, it has been possible to report upon two La Tène swords from the Historisches Museum of Basel. Sword number 1947–639 was found to be composed of very low-carbon piled wrought iron, in the as-forged condition. No attempt had been made to harden it by heat treatment. The hardness near the mid-rib was found to be 161 Vickers, increasing to 190 at the cutting-edge. Sword number 1947–640 is of good-quality wrought iron made from a large number of piled layers. A very rough estimate of these layers would indicate possibly some 50 to 100, many more than in the other sword. Again, the weapon is in the as-forged condition, and there is no evidence of hardening by quenching. The carbon content is variable. Near the central rib it is about 0.15 per cent., while close to the cutting-edge the carbon content rises to approximately 0.5 per cent. The hardness also varies from 161 Vickers at the low-carbon mid-rib to 286 in the coarse high-carbon zone at the cutting-edge.

We had hoped that these two swords would indicate that the La Tène sword-smith was familiar with the art of hardening and tempering. However, such was not the case, and we can only say that sword number 1947–639 is comparable to the La Tène sword from the province of Bergamo, examined by Storti and Mariani, that is, a sword of remarkably pure, but soft, wrought iron. Such a sword would be a very poor working weapon. On the other hand, sword number 1947–640 may be compared with the La Tène sword from Esino, also reported upon by Storti and Mariani, which is made from what may be described as a fair quality steel for its period. Such a sword, although not a 'quality' weapon, would be a working one, and possess certain advantages over the average bronze sword.

ROMAN CHISEL. *Chesterholm, England.*

This chisel was found by Mr. E. Birley during the course of his excavations at Chesterholm in 1932, and assigned by him to the second century A.D. (Pearson and Smythe 1931–7, pp. 141–5). The chisel is 8 inches

long with a square-sectioned body of about 0.4 inches. The following chemical analysis is given by Pearson and Smythe:

Manganese nil. Silicon 0.038 per cent. Phosphorus 0.016 per cent. Sulphur 0.011. Nickel nil.

Carbon was not determined analytically, for its distribution in the metal, as shown spectrographically, was so variable that an average value is of little or no significance. It will be seen that the metal is very pure, and there is comparatively little cinder; about half the chisel consists almost entirely of ferrite. The steely portions of the chisel consisting of pearlite and ferrite, or pearlite and cementite, appeared to vary from a dead mild steel to a high-carbon steel; the highest estimated carbon content observed was 1.3 per cent. About one-half of the chisel-edge consists of martensite and troostite, indicating that the edge of the tool has been heated approximately to 900° C., and then quenched in water. The absence of carbon in the other half of the cutting-edge nullified the hardening process locally. The report makes it clear that the hardening process had been confined to the cutting-edge. The authors made various hardness determinations with the Vickers machine. The average value of hardness in the metal comprising the body of the chisel, compared with the carbon contents roughly estimated from the structure at the points of indentation, are given as:

Carbon (per cent.)	.	.	0.0	0.1	0.2	0.3/0.4	0.5/0.6	1.3
Hardness. V.P.N.	.	.	136	114	149	169	214	233

On the whole, these figures agree with the values to be expected, though the hardness of the ferrite is higher than usual in unstrained metal. The deformed metal where the head of the tool has been hammered is of greater hardness, being 212 where the structure consists of ferrite only, and 218 where about 0.1 per cent. of carbon is present. The authors' remarks upon the heterogeneity of structure are of interest concerning the iron produced from the primitive smelting furnace:

In these, small blooms of pasty metal mixed with cinder were obtained, which with much hammering and many re-heatings were wrought into shape. Complete separation of cinder from metal was impossible, and the varying conditions in the furnace made it inevitable that some parts of the metal should be richer in carbon than others. Later forgings, though tending to equalization in composition, still left the metal streaky, bands of iron and of steel of varying composition alternating with one another.

While it is clear that the smith knew of the effect to be obtained from quenching, and possibly even aimed at some measure of tempering (compare with Carpenter and Robertson 1930, specimen No. 9, Egyptian axe), the Chesterholm chisel cannot be considered as a satisfactory piece of work. Because of the omission of adequate preliminary carburization, and the great variation in carbon content in different parts of the metal, about half the cutting-edge is martensitic with a hardness of 464 to 579 Vickers (say around 430 Brinell), while the other half consists of soft iron with a hardness of only 138 Vickers.

STEEL CHISEL. *Crayke, Easingwold, Yorkshire. Period, Viking.*

Report, by Dr. J. A. Smythe in *Hull Museum Publication*, No. 212, 1941, in a note, 'Metal objects made by the Vikings', by Thomas Sheppard.

'Cross-sections near the head, and side faces near the cutting-end, were examined metallographically. Near the head the metal consists almost entirely of steel containing 0.9 per cent. of carbon, in the condition, metallographically speaking, of sorbitic pearlite. However, there are patches of different composition, one containing about 0.4 per cent. of carbon, the other 1.2 per cent. of carbon, and each of these shows a well-marked Widmanstätten structure, which is evidence of heating to a high temperature, possibly 1,000° C. The hardness of this metal varies from 238 to 283 Vickers Pyramid Number. Near the blade of the tool, the structure is that of a quenched, high-carbon steel, consisting largely of martensite. The hardness is variable, but much higher than at the head, rising in places to the values 657, 782, and 870 V.P.N.

'It may be remarked that there are two essential processes in producing such a tool from wrought iron. The iron must first be carburized to a fairly high degree, and it must then be quenched from a temperature of 750° C., or above that. With respect to the carburization, this appears to have been done very satisfactorily, the average carbon content being that of a eutectoid steel (0.9 per cent. of carbon), considerable uniformity having been attained throughout, having regard to the fact that the steel was never melted. The hardening has also been skilfully done. It is clear that the tool has been heated to about 1,000° C. and only the cutting end hardened by quenching in water.'

The very high hardness figures at the blade will be noticed (compare with the Danish battle-axe of A.D. 895-6), and it would appear that the

temper had not been 'let-down'. Such a chisel would probably be too brittle for average heavy service upon the harder metals.

EGYPTIAN SICKLE. *Period, Roman, c. 2nd-3rd century A.D.*

Report. Carpenter and Robertson. 1930. Specimen No. 1.

The microstructure of the sickle blade was found to be typical of a low or medium carbon steel in the quenched and tempered condition. It was estimated that the carbon content varied from about 0.5 per cent. in areas of large grain size to about 0.35 per cent. in areas of small grain size. In the portion of the blade which was examined, the tempering had been carried out at such a high temperature that a very poor result was obtained. The Brinell hardness of the blade was only 116, and was not much harder than the back of the sickle, where the hardness was 96. Properly quenched and tempered, steel of the composition of this sickle should, of course, exhibit far greater hardness. As the authors state, the quenching and tempering had definitely spoiled the quality of the blade.

Tempering may approximately be controlled by observation of the oxidation colours, and without this guide the chance of successful tempering would indeed be remote. Even with modern knowledge of what the colours mean, it is quite easy to miss, or pass, the desired colour, and so have to repeat the whole operation in order to obtain a correct temper. Although he missed the temper, the smith who made this tool knew how to make comparatively pure and ductile iron and medium carbon steel. He also knew how to harden this steel by quenching and, further, how to reduce the hardness by tempering.

TANGED KNIFE. *England, Frilford, Berks. Period, 3rd-4th century A.D.*

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate XIII, Figs. 1-3, and pp. 189, 204.

The bulk of this blade had been converted to iron hydroxide, the only solid metal remaining being at the tang. Hence, an analysis was not possible, nor any determination of such matters as heat treatment, etc. A transverse cross-section showed a piled wrought structure and no doubt carburization had been used to increase the carbon content of the material, but no evidence was obtainable to indicate further stages.

TWEEZERS AND STAPLE. *Egypt, Harageh. Period, Roman.*

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate XII, Figs. 2-3, and pp. 188, 204.

This small Roman tweezers was examined in order to see if any special tempering was carried out in making the tool. The staple was examined as an example of Roman iron used for a non-cutting implement. The report states that the tweezer blades are made of a carburized wrought iron (carbon approximately 0.15 per cent.), with a Vickers hardness varying from 154 to 176. No special hardening technique appears to have been resorted to, but the medium degree of hardness attained should be quite well suited to give the springy material so necessary in a tweezers, and at the same time avoiding failure of the metal due to over hardening with consequent brittleness.

The staple was found to be made from piled wrought iron which carburization has brought into the range of a 0.25 per cent. carbon steel, the hardness varying between 189 and 336 Vickers. Such material should be well suited for a staple which might have to withstand considerable resistance while being driven home.

SHAFT-HOLE AXE. *England, Silchester, Hants. Period, Roman. 4th century.*

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate XIII, Fig. 4; Plate XIV, Figs. 1-3, and pp. 189, 204.

It was hoped that this very fine specimen of Roman shaft-hole axe would exhibit the technique of quenching and tempering. However, as Messrs. Stewarts and Lloyds' technical report shows, such was not the case, the hardness near the edge of the blade being only in the neighbourhood of 118 to 210 Vickers. In such a fine specimen it is perhaps surprising that the Roman smith should have been content with such moderate hardness for the cutting-edge of the tool. It is possible that it never was used, and would have been heat treated before being put into service. On the other hand, Mr. Whitaker has commented upon this point, saying,

The hardness figures we quote are as reasonably near the edge of the blade as we could get, and, of course, an axe with such a hardness would necessitate frequent sharpening. On the other hand, the carbide rich zones would give some measure of resistance to wear, particularly as the grain size in these areas is exceedingly fine. The damascene sword blades discussed by Colonel Belaiew in

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the Iron and Steel Institute Journal of 1918, No. 1 and 1921, No. 2 are hyper-eutectoid carbide steels with quite low hardness, the wear resistance being given by the carbides.

It is also quite probable that the user of the axe would have kept the cutting-edge in order by means of some measure of hammer hardening upon a field or other anvil. As we have mentioned elsewhere this is a well-known and undoubtedly ancient technique.

TANGED KNIFE. *Egypt, Oxyrhynchus. Period, Roman.*

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate XI, and pp. 187, 203.

This blade has been built up from a large number of faggots of wrought iron which had been forge welded in piles, leaving a blade exhibiting a wavy flow pattern. Numerous slag inclusions had not been expelled during the welding and forging. The material is exceedingly pure base wrought iron with a very low carbon content. No attempt was made to carburize or harden and temper the material. Neumann bands are observed in the microstructure, and have been formed by hammering the blade cold, after the hot forging. Such cold working is, of course, to increase the hardness which varies between 113 and 120 Vickers. Such hardness is typical of a modern low-carbon mild steel, and is harder than a normal wrought iron.

SHAFT-HOLE AXE. *England, Reading, Berkshire. Period, Saxon.*

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate XIV, Fig. 4, and pp. 190, 204.

As an example of Saxon metallurgy, this axe does not attain a high standard. The axe has been forged from a piled structure with layers of varying carbon content, but the hardness of the edge is only 154 to 165 Vickers, and there is no indication of quenching and tempering. While the carbon content taken from drilling from the heavy portion of the section near the socket was 0.23 per cent., it is interesting to note the extremely low carbon content of below 0.04 per cent. close to the edge of the blade as a result of prolonged heating which has decarburized the thin portion of the cutting-edge. Also, that the presence of Neumann bands in the ferrite grains shows the cutting-edge to have been heavily cold-hammered. There is no sign of quenching and tempering and this

axe would certainly not hold a sharp edge. It is clear that the smith was working in the dark, and had no skill in empirical methods of hardening, otherwise he would not have spoiled the cutting-edge of the tool through excessive decarburization. The heavy cold hammering, as indicated by the presence of Neumann bands, was probably an attempt to render an unsatisfactory tool in some measure serviceable.

BATTLE-AXE. *England, Essex. Period, A.D. 895-6.*

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate XV, and pp. 191-2, 204-205.

This shapely battle-axe is a fine example of smith's work. It is properly quenched and hardened as indicated by the Vickers hardness figure of 450 for the cutting edge, as compared with a figure of 160 to 170 for the body. The axe has been made from low-carbon (0.049 per cent.) sponge iron. A feature of interest is the relatively high hardness of the body which is due to the high phosphorus (0.445 per cent.) content of the iron. To render it suitable for hardening, the cutting-edge has been locally carburized. In manufacture, the iron has been piled and repeatedly forged from faggots of sponge iron; the fibre or grain flow being parallel with the cutting edge. The shaft socket has been formed by lapping over a tongue from the forging, and forge welding this to one side of the blade. While it is not, of course, in the same class as a fine damascene sword, we may say that this Danish axe sets a high standard of ordinary work.

SPEAR. *England, Reading. Period, Viking.*

Report. Messrs. Alfred Herbert for Reading Museum (Beeny 1950, No. 199).

This spear was examined because it exhibited a stippled or herringbone pattern. Evidence was obtained that the pattern had, in fact, been intentionally welded into the blade, and it could be classed as a simple example of pattern welding. A cross section of the spear reveals that the weapon has been compacted from about twelve longitudinal rods, apart from the stippled layers. The central regions of the spear contain little carbon and are very soft (97.4 D.P.N.—1 kilo load), whereas towards the blade edges the metal has as much as 0.45 per cent. of carbon, and the hardness is consequently greater (219 D.P.N.—1 kilo load). The hardness readings

vary with the carbon content and there is no evidence of any attempt to harden the steel by quenching.

SOCKETED ARROW. *England, Woodeaton, Oxon. Period, Mediaeval.*

Report. Stewarts and Lloyds. For Pitt Rivers Museum.

Plate XVI, and pp. 192, 205.

This barbed and socketed arrow has been made from wrought iron with only 0.05 per cent. of carbon. No attempt has been made to harden the arrow, nor would hardening be possible with such low-carbon material. The socket portion has been formed from thin wrought iron sheet wrapped round a pointed former. The barbs and point of the arrow have been imperfectly forge welded on to the socket. The Vickers hardness varied between 115 and 153. One would expect an arrow of this period to be of purely 'utility' manufacture. This specimen is a poor piece of work, although no doubt quite good enough for an arrow, but of little interest in the evolutionary series.

From the foregoing account of analyses the first point which will be noticed is the very early appearance of carburization, and the very appreciable increase in hardness of the metal so obtained. When we remember that an average hardness for wrought iron is about 100 Brinell, and that many modern low-carbon mild steels have a hardness of from 110 to 150 Brinell, it will be seen that a very appreciable increase in hardness had been attained in the two Egyptian knives of about 1200 B.C. These two specimens show that the smith of this early period had made considerable progress, and could already make hard and useful iron.

The second step of great importance is the introduction of quenching the carburized iron or low-carbon steel. This we find in the two Egyptian axes dated to about 900 B.C. In one of these axes (Carpenter and Robertson, specimen 9), heat transfer from the body of the axe gave a temper which left the cutting-edge with the remarkable hardness of 444 Brinell, which is approximately equivalent to the hardness of a modern carbon-steel cold chisel. The Egyptian axe is indeed a most remarkable achievement for 900 B.C. In a measure this result was no doubt accidental, for the hardness of the other Egyptian axe of 900 B.C., which was treated in a similar manner, did not exceed 229 Brinell. In the Egyptian chisel of 700 B.C. hardness does not exceed 302 Brinell, while the Roman sickle of the second to third century A.D. had been quite spoiled in an attempt to temper it. Even during Roman times it does not appear that there

was any uniform application of hardening to the various cutting tools in use. One would expect a razor to be hardened by quenching, but such was not the case with a razor of Roman period from Stockstadt am Main, Germany, which was subjected to metallographic examination which showed that the material had been treated by a cementation process, but was not hardened.¹ Not until we come to the Danish battle-axe of A.D. 890 do we find really satisfactory hardening and tempering. When it was found that quenched iron, or rather quenched steel, was too hard and brittle for normal use the natural reaction of the smith would have been to try heating, so long associated with the softening of copper, and he would find that this did indeed soften his quenched material. We do not know how and when he discovered the colour guide to the temper ranges which are so necessary to control the temper. Of all the heat treatments, this operation would be the most difficult to perform, and for a long time its successful application may have remained the secret of a few smiths in selected regions of advanced metallurgy.

The preparation of a forging by forge welding together a number of layers or laminations of wrought iron, so giving a piled or compacted structure, was a most important aid to good carburization. It is noteworthy to find this practice attested so early as the eighth century B.C. (in the tripod from Nimrud), followed by the fine spear from Deve Hüyük, in Syria, at 600–500 B.C. After this time, no doubt, piled wrought iron was frequently used for making good quality tools and weapons which required to be hardened. Concerning forgings made from piled wrought iron, Mr. Whitaker has kindly given me a most interesting note:

During heating for forging iron is preferentially oxidised to the copper, nickel, arsenic, phosphorus and other elements present even in small amounts which are less easily oxidised, so that the surface of the heated iron becomes enriched in these less easily oxidised elements. After many heatings the immediate surface of the iron can become so enriched that the analysis of the surface is very different from that of the main mass. After welding and piling the pilings can be counted and the resulting water markings or flow pattern clearly seen. See our report on the Syria, Deve Hüyük spearhead, Fig. 44, and the Silchester Roman axe, Plate XIII, Fig. 4. This surface enrichment due to the preferential oxidation of the iron sometimes results in iron which does not scale as quickly or corrode as quickly as the base material underneath the enriched surface layers. For instance, it is possible by heating a copper-bearing iron, say with only about 0.3 per cent.

¹ See *Freiberger Forschungshefte; Kultur und Technik*, D 6; Bernhard Neumann, *Die ältesten Verfahren der Erzeugung technischen Eisens*, Akademie-Verlag-Berlin, 1954, pp. 58–59.

copper in certain ranges of temperature, so to enrich the surface layers in copper, due to the preferential oxidation of the iron from the surface, to form a layer of nearly 100 per cent. copper on the surface, so that the faggot is coated with copper. Such surfaces are often very resistant to corrosion.

The specimens at our disposal are too few to permit of accurate conclusions being drawn as to the technical progress made in the various periods, but they serve to show the reason for the general expansion of the industry after about 1200 B.C., and the fact that there was relatively steady progress culminating in the fine swords of the Hallstatt period. We know that the best La Tène smiths were highly skilled in artistic work, but we have insufficient metallurgical evidence about the quality of the La Tène swords to be able to make any general statement. The examinations of La Tène material which we quote are disappointing in that they do not show any exceptionally high standard in iron metallurgy. We do not find support for Déchelette's view that La Tène swords were of highly advanced technique. However, without the examination of much more La Tène iron it would be unwise to be dogmatic upon this particular point. In general it is perhaps true to say that, from 1000 B.C., we must await the crucible steel of the East, and the damascene and pattern-welded swords, before we find the highest skill developed by the smith, coupled with really outstanding metallurgical progress.

In the West, the Roman smiths do not appear to have made very marked progress in actual technology, but rather appear satisfied to retain the old and well-established techniques, while much increasing the productive capacity of the iron industry. As the following examples indicate, it is true to say that by the Roman period very substantial iron forgings could be made.

Early Iron Forgings of Considerable Size

Perhaps the most famous iron forging of great size is the Delhi pillar. The figures given by various authorities as to the dimensions of this column do not always agree, but the following figures given by Richardson (1934, p. 581) may be taken as reasonably correct. The shaft itself is 12½ in. in diameter at the top, and 16½ in. in diameter at the base. It is nearly 24 feet long and weighs by estimate somewhat more than 6 tons. The date is usually considered to be approximately A.D. 300. Owing to the limited capacity of the smelting and forging furnaces available, it is obvious that a forging of over 6 tons in weight could not have been produced from one bloom of wrought iron. Hadfield

(1912, pp. 153-8) has given much information concerning the Delhi pillar which was probably forged together from a number of small billets each weighing around 80 to 100 pounds. The pillar has been kept in remarkably good condition, and free from corrosion. Hadfield gives the composition as:

Carbon 0.08 per cent. Silicon 0.046. Sulphur 0.006. Phosphorus 0.114. Manganese nil. Iron 99.72. Total 99.966 per cent.

The material is a very good quality wrought iron, the low sulphur content of 0.006 per cent. indicating that a very pure fuel, almost certainly charcoal, was used in its manufacture and treatment. Wrought iron usually contains at least a trace of manganese, but the Delhi pillar did not apparently contain that element. According to Hadfield, the Dhār, or Dhārā, iron column (at Dhār, the ancient capital of Malava, thirty-three miles west of Indor) is of even greater size than the Delhi pillar. Three existing pieces measure 24 feet, 12 feet, and 6 feet in length, making an original length of some 42 feet.

In Europe, some large and heavy forgings of Roman iron are known. In the Roman settlement at the Saalburg, Germany, a forging of over 4 feet in length by about 5 in. square was found (Jacobi 1897: Taf. xlvii, pp. 237-8, 251, 258, 554). Also, three very heavy blocks of iron were found which had been used as window frames. Of course, such could not have been their original purpose, and they have the appearance of perhaps being rough-outs for making unusually large and heavy anvils. Another very large piece of iron is the anchor from Lake Nemi in Italy. This anchor belonged to a boat which has been ascribed to the Roman period. It was apparently forged from three billets and the whole weighed about 1,275 pounds (Speziale 1931, pp. 309-20; Calbiani 1939, pp. 359-70). At one time, what was thought to be the largest known mass of Roman wrought iron was the bloom found on the site of the Roman Corstopitum, near Corbridge on the north bank of the river Tyne (Bell 1912, pp. 118-35). It was found in what appeared to be a reheating furnace, and measured 39 in. in length. It is approximately 7 in. by 8 in. at one end, tapering to 5 in. by 4½ in. at the other end, and weighs about 340 pounds. The bloom had been built up by forge welding together a number of smaller sections which, according to Stead's examination, did not exceed a unit weight of 40 pounds. The whole block was probably used for an anvil. Analyses of the Corstopitum bloom gave the following average composition:

THE TECHNICAL ART OF THE SMITH TO ABOUT A.D. 1000

Chemical analysis, average, by Dr. J. E. Stead.

Carbon 0.097 per cent. Manganese 0.04. Silicon 0.046. Sulphur 0.025.

Phosphorus 0.044. Copper 0.01. Arsenic 0.049. Cinder 0.380 per cent.

Even larger blooms of Roman iron have been found at the Roman Villa, Chedworth, near Cheltenham, Gloucestershire, of which the Curator, Mr. Norman Irvine, has kindly furnished the following particulars.

In the museum at the Chedworth Roman Villa there are three large blooms of iron. There cannot be much doubt that the blooms are of Roman origin as they were all found in a chamber in the north-west corner of the Villa, and there is very little evidence of a later occupation of the site. The following are the weights and dimensions of the blooms. The dimensions are given to the nearest half inch for length, and quarter inch otherwise. The weights are taken from an old guide book and due to loss by rust and scaling they are now perhaps on the high side, especially for numbers 2 and 3.

No. 1. Length $63\frac{1}{2}$ ". $8\frac{1}{4}$ " \times $6\frac{1}{2}$ ". Weight 484 pounds.

Shape. Like a cigar. Centre portion of 'square' section with unequal taper to the ends. The cross section is circular at, and near, the ends. This is the best bloom, and appears to be in original condition.

No. 2. Length 37". $7\frac{1}{2}$ " \times $7\frac{1}{4}$ ". Weight 356 pounds.

Shape. Square section right through with slightly enlarged ends. One end is in original form, the other end evidently had been broken to provide metal for some purpose. The break appears to have been made 'cold'.

No. 3. Length $37\frac{1}{2}$ ". $6\frac{3}{4}$ " \times $6\frac{1}{2}$ ". Weight 256 pounds.

Shape. Roughly of square section. There is a slight taper from one end to the other, the larger end shows a fracture similar to that of No. 2. There appears a possibility that this bloom is half of an original similar to No. 1.

Wootz Steel and the Damascene Process

Finally, some reference must be made to the various damascene processes and their relation to Wootz steel of ancient origin. This is a complicated matter which has occasioned some measure of confusion in archaeological literature. A complete discussion of the various processes would be impossible within the space at our disposal; hence, the following notes must be limited to a general description of the major techniques employed. Given appropriate heat and mechanical treatment Wootz, the ancient Indian crucible steel, furnishes a true damascene pattern. Of this Professor Desch (1937-8, p. 191) has said:

The true Eastern Wootz process was essentially a crucible process. The material was enclosed in a kind of crucible and was run down into a cake,

which had to be exposed to a blast to render it malleable. . . . The true Damask steel was obtained first in the molten state; the very coarse crystals were formed in the molten mass and were forged out at a low temperature. That was quite different from the false Damask, which was made by welding together soft and hard steel.

We are justified in referring to the damask of the Wootz steel as a true damask, or damask of crystallization. Again, we also have the damascene patterns which were made by welding together either soft and hard steel, or pure iron and carburized iron. Also, there is the delicate forging operation which has been termed by Mr. Maryon 'pattern welding'. Finally, there is the false damascene effect which may be obtained by chemical surface treatment of the metal.

Rickard (1932, ii, pp. 863-5) considers that the earliest real steel was probably the Indian steel known as Wootz. This steel was exported from Mysore, possibly even before the beginning of the Christian era, and may have been known to the Roman world. It was smelted from natural magnetite sand, or some similar material, which had been washed and ground to a small size.

From Rickard's account it would appear that two processes were involved, first a smelting operation, and secondly a crucible process. The smelting was carried out in a small furnace about 4 feet in height, charcoal being used as fuel and no flux added to the charge. The furnace was of the usual rather conical form with clay tubes inserted near the base of the furnace to serve as blast nozzles which supplied forced draught. Slag was tapped at intervals during the course of smelting. The bloom obtained as a result of the smelt was a malleable iron with much included slag; so far as possible the slag was expelled by heating and hammering subsequent to the smelting. The efficiency of conversion was very low, a magnetite with an iron content of 72 per cent. yielding only 15 per cent. of its weight in bar iron. In the crucible process, the refined iron which had been obtained from the smelting and hammering operations was cut into small pieces; these pieces, to a weight of about 2 lb., were packed into clay crucibles in which some dry wood and green leaves were also included. Before firing, the crucibles were, of course, sealed with clay. Of the subsequent operation Rickard says:

Two dozen such crucibles were piled together in the form of a cone in a small furnace, into which charcoal was fed. This being lighted, a blast was maintained for $2\frac{1}{2}$ hours; then the crucibles were removed, allowed to cool, and broken, yielding cakes of steel. These cakes were then heated for several hours at a

temperature just below melting, during which time they were turned over in a current of air from the bellows, so as to expel any excess of carbon and to produce a low fusing point. Finally the cakes were hammered into short bars ready for sale to the traders.

In a later paper Rickard (1939, pp. 100-1) again mentions Wootz steel, and points out that the Damascus blades, long associated with steel of ancient origin, were made from Wootz steel of Indian origin. Rickard says that the steel was made by the Chera Tamils in Hyderabad, and was exported from India shortly before the Christian era. It would seem that the cakes of steel obtained from the crucible process contained 1.33 per cent. of combined carbon, and 0.31 per cent. of uncombined carbon. For export, the cakes were no doubt forged into short bars.

Richardson (1934, pp. 580-1) is in agreement with Rickard in considering that Wootz steel was made from the black magnetite sands of Hyderabad, that it was exported, and was much prized by the Romans. He differs from Rickard in thinking that the manufacturing process was entirely a crucible one. In Richardson's own words:

The charge, consisting of black magnetite ore, bamboo charcoal and the green leaves of certain carbonaceous plants, was sealed in a crucible made from native clay. Several of these would be set in the hearth which was then filled with charcoal and the furnace lighted. Gradually raising the temperature to a point when the charge became molten (approximately 3000 deg. F.), an iron-carbon alloy was thrown out of solution and solidified in mass at the bottom of the crucible. This metallic button or mass, mechanically separated from its slag, was then alternately melted and cooled again four or five times, each complete operating cycle requiring a day. Then in round cakes about five inches in diameter and one-half inches thick, each of them weighing approximately two pounds, the metal was carried overland by caravan to the arms-making centres of western Asia, or if for export, to the various shipping points. A long normalising treatment preceded the forging operation which was done with great care, flowing the metal in two or more directions with light blows of the hammer. After prolonged annealing the blades were quenched and drawn to the desired hardness, then polished and etched. This last operation brought to the surface the damask inherent in the steel; and its pattern and background colour determined the quality.

Also made by a crucible process is the Persian steel, but in this the charge, which was treated in crucibles, was wrought iron and charcoal.

Forbes (1950, pp. 410, 437-8) mentions the production of Wootz steel through smelting the contents of clay crucibles which before sealing were charged with black magnetite ore, bamboo charcoal, and leaves of certain carbonaceous plants. As we have previously mentioned, this

operation gave the Wootz cake of steel. In a subsequent operation to make the Damascus blades the cakes were forged by flowing the metal in two or more directions, annealing, quenching, and tempering. Finally, the damask pattern was brought out by polishing and etching. Forbes points out that there are different descriptions of the Wootz process. For instance, Ure (*Dictionary*, vol. iii, 1867, p. 764) considered the ore to be first smelted in a bloomery furnace using charcoal as fuel, and with forced draught supplied by means of bellows ending in bamboo tubes feeding tuyères of clay. As described by Rickard, a crucible process then gave the cakes of Wootz steel. If the steel was not for export, but was worked on the spot, it was frequently forged and then polished and etched with acid to bring out the damask pattern, afterwards being glowed at a temperature not exceeding 700°C. , and allowed to cool slowly.

From these various accounts of the making of Wootz steel, it will be observed that the process is a complicated one and must have been of long standing, the result of many years of experiment, trial, and error. In view of the technical difficulties of the process, and of the reference to alternate melting and cooling of the steel, it appears impossible that such steel should have been made in pre-Roman times. Concrete dating evidence appears to be absent, and one may well doubt if the whole technique was known to the Roman metallurgist. The production of the steel itself was far from simple, and the discovery of the subsequent technique of cross forging and etching in order to give the damask pattern would be noteworthy even in the Middle Ages.

Damascene Steel

Thanks to the valuable research of Col. N. Belaiew (1918, pp. 417-37), the methods by which the damask patterns are produced on some steels of ancient origin have been made clear. According to Belaiew there were three modes of making the true damascene steel:

- (i) The old Indian. The steel being made by a crucible process using pure ore and the best kind of charcoal.
- (ii) The, say, Persian. Here the crucible charge was of iron bars and charcoal or plumbago.
- (iii) A heat treatment of steel, resembling very prolonged tempering.

A real damascene steel with its macro-structure appearing on a polished surface must not be confused with a 'wrought' damask which has been

produced by welding together a compound of iron and steel bars and wires. Full particulars and technical details of the damascene steel made by Belaiew will be found in his paper for the Iron and Steel Institute. In essence, the steel was prepared by placing a mixture of soft iron and graphite in the crucible which was heated for a period of more than two hours after the charge had melted; the damper was then closed and the hearth plastered up so as to retain the heat. Hence, the alloy cooled down slowly in the crucible together with the furnace. Such delayed cooling is an essential feature of the process in order to obtain the desired crystalline structure in the steel. The alloys prepared by Belaiew in this manner had carbon contents ranging from 0.45 to 1.80 per cent., and even more. A fine Oriental blade with a large motley pattern showed the following composition upon analysis (Belaiew, 1918, p. 427, and Fig. 2).

C	Mn	Si	S	P
1.49	0.08	0.005	0.05	0.10 per cent.

Analyses of other blades showed the carbon content mostly between 1.20 and 1.80 per cent. with, in a few cases, occasional drops to *hypoeutectoids* with 0.60 to 0.80 per cent. of carbon. Not only had the composition of the steel from which the ancient Oriental damascene blades were made to be within certain limits, but the further heat treatment and forging were of the greatest importance. On this point Belaiew stated that,

The alloys were, first, pure iron carbon alloys, mostly hypereutectoids and very rich in carbon; secondly, they were alloys of crucible steel, subjected to the highest possible degree and duration of heating and then slowly cooled down together with the furnace; thirdly, they were forged, quenched, and tempered very carefully, and never exceeding certain limits of temperature.

A very great amount of mechanical treatment, or forging, was expended on the best class of Oriental blades. According to the quality of the damask, and the skill of the workman in forging and cross-forging, wavy, motley, and vertebrae patterns were produced. Apart from the beauty of the finished work, damascene steel had also exceedingly practical advantages. When properly made, the steel was very strong and possessed a very high elastic limit. For instance, a good blade could not (in the ordinary sense of the term) be broken by bending, it could be bent to a right angle without breaking or losing its elasticity. Again, owing to its temper, an unusually sharp and durable cutting edge could be imparted to the blade.

In a contribution to the discussion upon a paper by C. H. Desch and

A. T. Roberts (1923) entitled 'Some Properties of Steel with Globular Cementite', Colonel Belaiew made the following remarks which further clarify the technology of damascene steel.

On two occasions, the authors (Desch & Roberts) stated, they were unable to develop the damascened structure, in spite of the fact that the cementite was entirely spheroidised. The structure of the damascened blades, however, was not the result of the spheroidised structure of the cementite particles; their structure, as was known from the blades in several collections, was the result of the primary structure of the damascened cake. There must be a certain agglomeration of masses of cementite parallel to the axes of the primary crystals in order to show that structure after forging. He suggested, therefore, that one of the possible reasons why the authors were unable to develop the damascened structure was that the primary structure and the axes of the crystals were not sufficiently developed. The old Indian maker was always at pains to produce, first of all, in his damascened cake that primary structure, and only afterwards, with infinite pains, did he try to forge his disc in a certain manner to develop that redistribution of the axes of the primary crystals which would show the wavy structure. The mechanical properties of damascened blades were due, to some extent, to that primary structure, and that was the reason why the damascened structure always appealed so much to the Asiatics, and to a certain extent even to Western metallurgists.

The importance of the microstructure, or the importance of getting the cementite spheroidised, lay in the fact that the carbon content in the old damascened blades was so high that it was impossible to forge such high carbon steel when the cementite was in needles in such big agglomerations. It was quite impossible to forge the steel with all those protruding needles, and, in order to be able to forge such a blade, it was first imperative to spheroidise the cementite. That spheroidisation of the cementite was carried out quite fortuitously by the subsequent forgings and heatings which formed a part of the old process. It was impossible to forge a large, or even a small, cake at once, because the heating arrangements were deficient; the temperature would never exceed, say, 800° C., and, during the forging, it would cool down after a few minutes. The first forging, therefore, would only result in that preliminary breaking up of the cementite lamellae. Afterwards, when the cake had cooled down, it was reheated and forged again and again, and all these forgings and heatings (which were applied, of course, quite unconsciously by the old smith) resulted in the breaking up of the cementite needles and the spheroidisation of the cementite. . . . In many tools, if the carbon content was high, the maker was, consciously or unconsciously, getting that damascened structure of spheroidised cementite, and the same was true to a certain extent in the case of alloy tool steels. . . . The structure of many blades and many tools, when their carbon content was high, was exactly the same structure as was unconsciously arrived at in India and Persia many thousand years ago.

As we have seen, the ancient Indian crucible steel known as Wootz

became known to the Romans. Clearly, it was highly prized, for a pure crucible steel would have been far in advance of any of the wrought irons, or semi-steels, of the western countries. Made from the same Indian crucible steel, true damascene steel probably did not appear in Western Europe until the Middle Ages. In spite of the fact that the basic material for making damascene steel was possibly known in India even before our Roman period of the West, it is not surprising, when we consider the complex and controlled metallurgical and mechanical processes required for the production of a true Damascus steel, that its appearance in Europe may well have been delayed until much later times. In the author's opinion it is a matter for wonder that so elaborate a technique should have been evolved so far in advance of modern knowledge of the structure and properties of steel.

Pattern Welding and Damascene Steel

A very complex forging technique, and one of extreme difficulty of execution, is known from about the third century A.D. to the Viking period. A large number of iron swords excavated during the years 1858 to 1863 from Nydam Moss, Schleswig, Denmark, were found to be decorated with twisted patterns giving a herringbone effect, the pattern being wrought into the material of the sword itself. This particular technique has been investigated and termed by Mr. Maryon 'pattern welding'. A sword of Nydam type has been recovered from Ely Fields Farm, near Ely, Cambridge, and has been reported upon by Maryon (1943-7, pp. 73-76). In general, the decoration of these swords is formed by a central band, or bands, composed of twisted rods, or bundles of flattened wire, running parallel down the length of the blade; the cutting edges, core, and twisted strips are welded together in one mass. The Ely Fields sword was composed of members forming the two cutting edges, then a separate core, and on either side of the blade the decoration formed from four twisted rods or bundles of strip. In the course of his research Maryon made experiments to copy this sword, and the extreme delicacy of the work is well indicated by his remark: 'The strips for that work must have been of metal not thicker than $\frac{1}{100}$ of an inch. And, moreover, careful examination shows that about two-fifths of the outer surface of the twisted rods was ground away after the welding was completed. This would be done during the grinding and polishing of the weapon.' As Maryon points out, the welding of these swords was excessively difficult, and it is indeed hard to see how complete fusion of

the delicate strips which had to form the pattern was prevented. Today, such delicate work is a lost art.¹

In 1950 the Ancient Metallurgy Committee of the Royal Anthropological Institute arranged the examination on behalf of the Reading Museum and Art Gallery of a Viking period spearhead, probably derived from the bed of the River Kennet at Reading, which exhibited a herringbone pattern. Various points of interest were brought to light by the report (Beeny and Collins, 1950). First, it is of interest to note that very thin strips of soft steel were used for the decoration. These rippled strips running down the spear averaged about 0.015 inches in thickness, but in places increased to 0.025 inches. There was no orderly twisting of the strips as in the Nydam swords to account for the rippled pattern. Secondly, examination of a cross section of the spear revealed that the weapon had been compacted from about twelve longitudinal rods, apart from the stippled layers. It is not easy to see why the smith should have built up the central core of the spear from various layers of very soft low-carbon iron unless this technique be due to a desire to obtain a better penetration of carbon (by forging, or even by a cementation process) than could have been achieved had the spear been made from a solid forging. It is clear that a relatively high carbon content could be imparted to a number of thin laminations, and therefore a temper giving the spring-like steel so desirable to a good sword or even spear could be attained.

A structure compacted from a number of laminations is known in other contexts. In a spear from Deve Hüyük, Syria, dating to 600–500 B.C., it is estimated that the blade was built up from about fifty layers of sponge iron plates (see Cap. VII, pp. 137–8).² Again, in more recent times the compacting method was highly developed in the manufacture of Japanese swords. Dr. Chikashige (1936, pp. 90–92) speaks of a very great number of laminae in certain swords of high quality. The Reading spear does not appear to be pattern-welded in Maryon's sense of the term, but it may well be a degenerate form of the technique.

Damascene patterns exhibited by certain Merovingian and Carolingian

¹ For a further discussion of damascene steel see Neumann (1927, pp. 241–4) where the following analysis of one of the Nydam damascene swords of the Roman period is given:

Carbon 0.62. Silicon 0.15. Manganese 0.363. Phosphorus 0.054. Sulphur 0.073. All figures are expressed as percentages.

Again, for a technical discussion of sword-making, both plain and damascene, see Sommer (1924, pp. 127–43).

² This chapter also discusses other implements which exhibit a piled structure.

swords have been studied by Albert France-Lanord (1949, pp. 19-45). These swords are made by a delicate technique of welding and forging. On reflection, France-Lanord considered that the hypothesis of making damascene blades by surface welding of thread-like elements presented considerable difficulties, and a forging test led him to consider that such a procedure would be impracticable for the making of a whole blade.

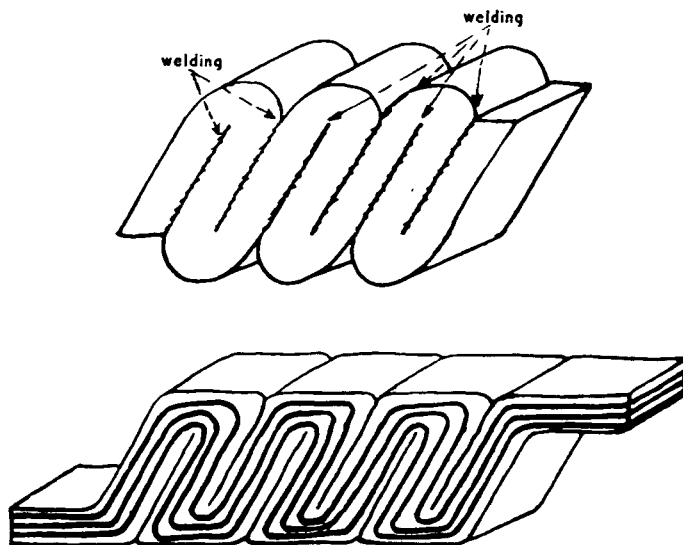


FIG. 46. Welding a damascene sword from pure iron folded with carburized iron (France-Lanord 1949, Figs. 5, 6).

His view upon the method of manufacture for the Merovingian and Carolingian swords is as follows:

Examination of a damascene blade shows a network of zones of pure iron and carburized iron. This network only covers the central part of the blade and is sharply separated from the cutting-edges which are in homogeneous iron. The line of separation between the central zone and the cutting edges is a weld; at the centre of the central zone runs another weld. Hence, the two cutting edges are welded to the central damascene zone. Also, down the length of the sword the central damascene zone is welded at its centre; in certain swords the central zone may be formed of two, three, or even four, welds. Micrographic examination (Pl. I, Fig. 1), showed that the metal in the pure iron zones was very pure, containing only some small inclusions. The carburized parts appeared as a hypoeutectoid steel of variable carbon content of 0.1 to 0.4 per cent., the

mean of 0.2 per cent. corresponding to an extra mild steel. France-Lanord postulates that the central damascene zone was made by a band, or rod of iron, composed of a laminated structure (pure iron and carburized iron), which was bent on itself (Fig. 46), each fold being welded to the preceding fold so as finally to form a bar of a certain length of which the structure is at the same time stratified and folded. The welds

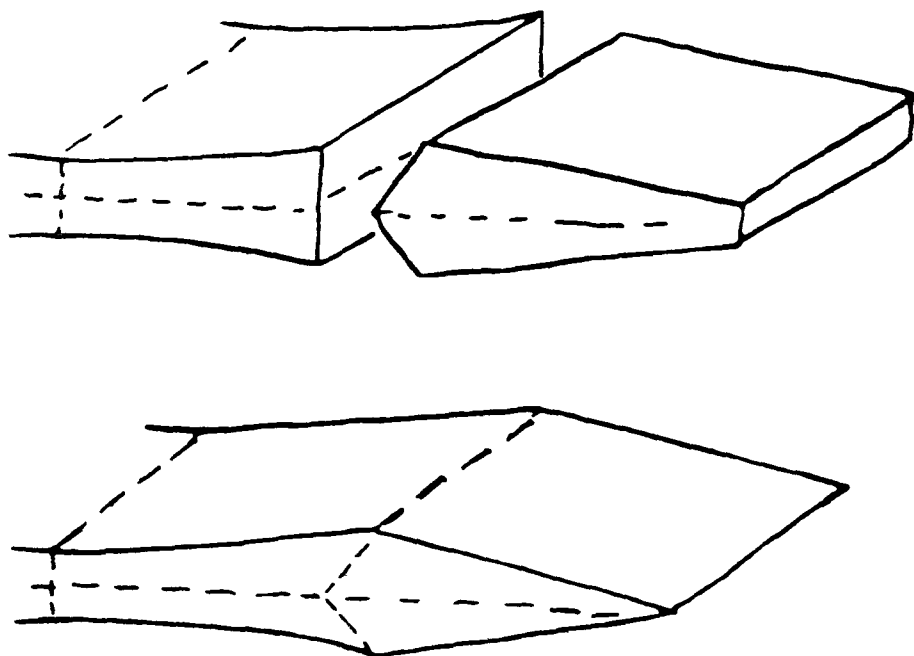


FIG. 47. Welding a hardened cutting-edge on a sword (France-Lanord 1949, Fig. 12).

were perfectly made and difficult to detect; some could not be seen. The bar was much forged and returned many times to the fire.

To give the bar its laminated nature, before folding it, it could have been made of three thin bands of iron of which the surfaces had been carburized during the process of forging. It is also possible that one wide band of iron was folded three times in its width, so as to make a single bar when forged. This bar would again be folded lengthwise as mentioned above. The cutting-edges of the sword, very slightly carburized, are welded to the central portion (Fig. 47) in such a way as to augment the surface of the weld and its solidity; the blade shows a swelling at this point. Towards the end of the sword, the cutting-edges join and terminate in the usual point. The metal of which these swords are made is pure

iron. No trace of tempering was found in any arm studied, and tempering would have been impossible because the carbon content is not high enough. By submitting swords in fairly good condition to deflection tests France-Lanord found that the mean resistance of damascene blades is 2.5 to 3 times that of ordinary swords. The conclusion is that the long and delicate forging and welding work in the damascene blades increases the elasticity and resistance. It is not the nature of the metal which is better, but the method of working it which enables improved results to be obtained. The hardness of the cutting-edges was obtained by long and careful hammering. Recent work (Klindt-Jensen 1952, pp. 218-28) shows that the Merovingian technique is traditional. In the great deposit at Vimose in North Jutland were no less than eighty-four swords, of which a number had pattern-welded blades, and they may be ascribed to the Roman period. Examination of a pattern-welded central portion showed it to be fashioned of weld-steel of two degrees of hardness, hard steel being used for the edges and spine of the blade, while the remainder consists of layers of hard and soft steel to give the blade strength and resilience. According to the author, this examination demonstrated methods of manufacture identical with that of the Merovingian weapons.

From the sixth to the eleventh centuries, according to France-Lanord, all good swords were made by the above method. Afterwards the technique was replaced by steel swords which became general. Nevertheless, the utilization of welded damask in quality arms continued through the centuries in various countries, and it was thus that the celebrated damascene gun barrels were forged until recent years, in particular in Belgium around Liège. At the present stage of our knowledge it is impossible to define the place of origin of the welded damascene blades. Several authors have thought they may be of Oriental origin and they have brought together the western welded damask and the eastern damask, or damask of crystallization, of which Colonel Belaiew has defined the nature. The Oriental blades, of hypereutectoid steel, have a high carbon content and are forged from a block of steel made in a crucible. The watered appearance of the surface of the blade comes from the crystalline structure of the metal itself. One cannot usefully compare the two techniques, and one must admit that the welded damascene technique examined by France-Lanord is the result, as he says, of an evolution made in western countries to improve the forging technique and permit the manufacture of good-quality weapons from metal which was only iron.

The Art of the Sword-smith in Japan

To conclude our review of the technical art of the smith, it is appropriate to mention the work of the famous Japanese sword-smiths. The finest Japanese swords are not of such early date as the damascene work which we have previously mentioned, but in their basic technique they certainly go back to the thirteenth century A.D., and may well be considerably more ancient.¹ This work must be classified as of the highest quality, and called for exceptionally highly trained and skilful smiths. A comprehensive account of the long line of qualified Japanese smiths will be found in the work of Joly and Inada (1913, pp. 69 ff.). They explain that such swords were forged from iron and steel welded together in various ways, the raw materials used being of Japanese origin except in the case of the so-called Namban Telsu swords. According to the authors the iron was smelted from titaniferous ores and from magnetic oxide. Charcoal smelting was used and an exceedingly pure metal obtained, the small proportions of phosphorus, manganese, and silicon being especially noticeable. The final operation of tempering the blade was of great importance and it is stated that

The aim of the smith was to produce the hardened steel at the edge only, so that the blade retained a greater amount of toughness than if it had been hardened throughout. Hence the admixture of iron, which does not harden in the tempering process, and the use of a protective covering of clay (*sabidoro*) over part of the blade before hardening it. In European practice steel blades were hardened, then rubbed with some abrasive substance, so that the metal surface became bright, and then the temper drawn down to one of the 'colours' produced by the formation of a film of oxide, characteristic of certain degrees of hardness. The modern style of scientific tempering consists, however, in raising the metal to a definite heat, and in quenching it at that temperature. The Japanese swordsmith proceeded in precisely the same manner: the blade was heated over a fir-charcoal fire until it reached the desired heat, gauged by its glow and colour. It was then quenched.

The preparation of ancient Japanese sword steel of high quality has been very clearly described by Dr. Chikashige (1936, pp. 85-101), as follows:

A piece of steel is first forged as a foundation, and to this a long rod of iron is welded to serve as a handle. Then another piece is heated and quenched in water, after which it is broken up and placed on the foundation piece; these are then heated and welded to form one sheet. See Fig. 48 (after Chikashige, diagrams on pages 90 and 91). The object of this process is probably to produce the

¹ The Pitt Rivers Museum has a sword by Iyetsungune, dated about A.D. 1138.

THE TECHNICAL ART OF THE SMITH TO ABOUT A.D. 1000

isotropic structure of the resulting steel. This sheet is now notched in the middle, the notch being at right angles to the centre line of the handle. Next, one half is folded over and the two welded together; this is the first welding of the folded

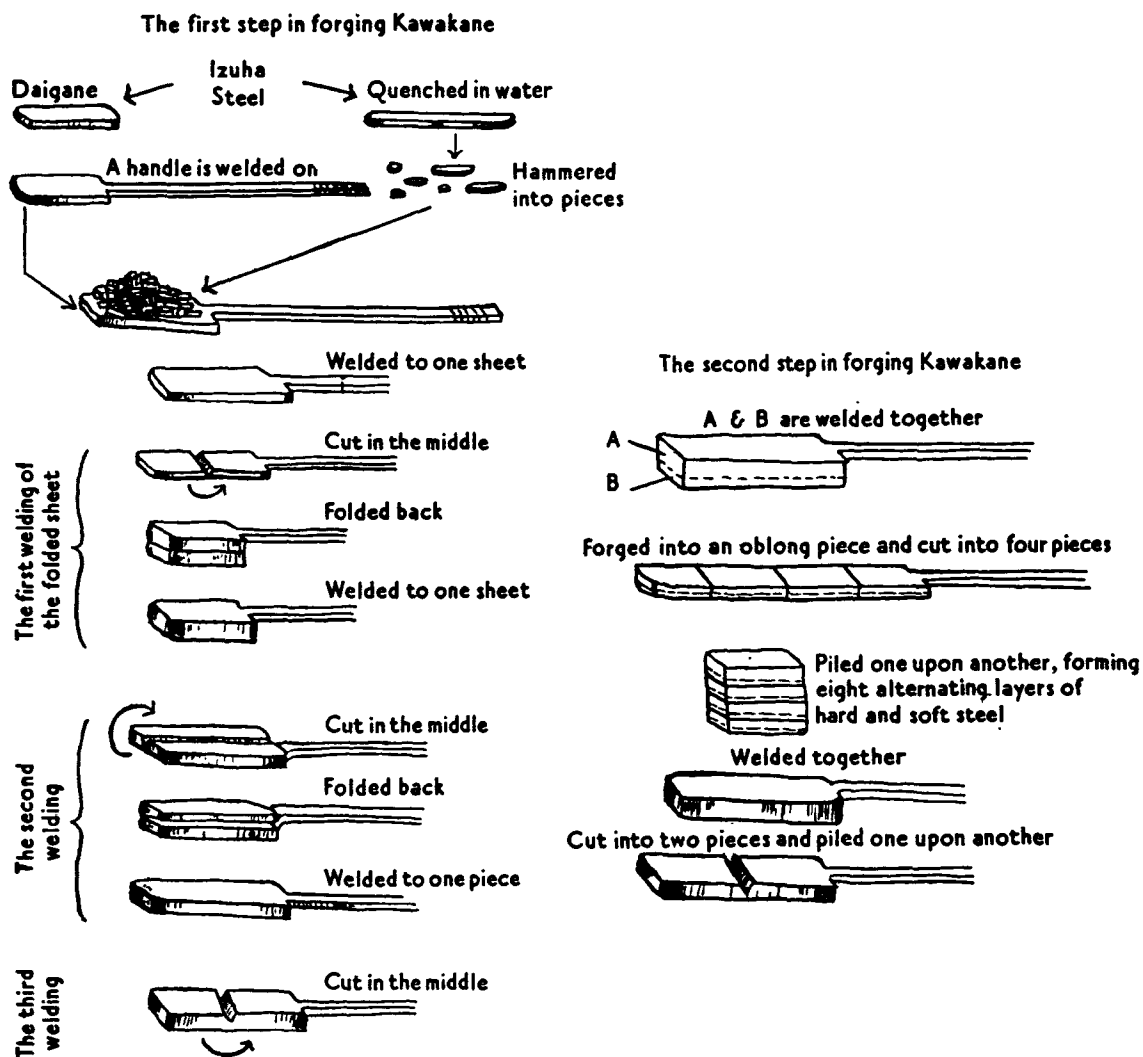


FIG. 48. Forging Japanese swords (Chikashige 1936, pp. 90-91).

sheet. The sheet is again notched in the middle, but with the notch parallel to the centre line of the handle, folded over, and the parts welded as before. This is termed the second welding of the folded sheet and the process is repeated about ten times, resulting finally in a rectangular sheet which may be termed *A* (see Fig. 48). Next, a piece of soft iron is subjected five times to the 'welding of the

folded sheet' process, and forged to the same shape as *A*, but with only half its thickness; the resulting sheet is shown as *B* in the figure. *A* and *B* are now welded together, forged into a billet and cut into four equal pieces which are then piled one upon another and welded together. The resulting block is again cut in the middle, piled as before, and again welded. The forging now consists of sixteen alternating layers of hard and soft steel. The process as above described is further repeated, the number of layers being multiplied by each repetition and after, say, ten repetitions the steel acquires a fine laminated structure; the number of the laminae being as many as sixteen thousand in one inch thickness of metal. When the welding has been skilfully carried out the effect of the

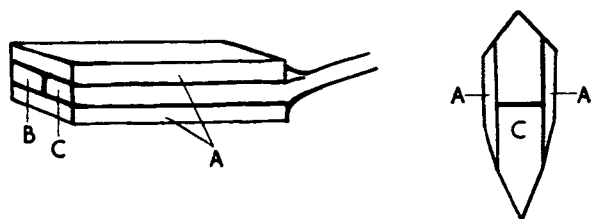


FIG. 49. Forging a Japanese sword (Chikashige 1936, p. 94).

diffusion of carbon is predominant, and apt to cause the boundaries of the hard and soft steel to be obliterated. As a consequence, the laminated structure may be almost indiscernible. It was commonly said among sword-smiths that excessive repetition of the folding and welding process was rather harmful.

A complete sword is forged together from three separate sections, cover, centre, and edge. The highly folded metal just described is known as 'cover metal', while the 'centre metal' should be composed of soft steel alone, which has been subjected to the welding and folding process, but not to the same degree as in the case of the cover metal. The edge metal is composed of hard steel. Fig. 49 (Chikashige 1936, p. 94) indicates what may be termed the standard method of forging a sword from the above-named pieces of steel. Two cover pieces, one centre piece, and one edge piece are used in combination, the centre and edge pieces being welded together before hand. Next, the three pieces are piled, welded together, and forged down to give the final shape of the blade. The ideal section of a blade forged in this manner is shown in the figure, and the actual section approaches this more or less according to the skill of the smith. According to the school of the sword-smith, other combinations for building up the blade may be used. We cannot go into detail here, but a discussion of other methods of forging, together with macrographs of sections taken from various swords, will be found

THE TECHNICAL ART OF THE SMITH TO ABOUT A.D. 1000

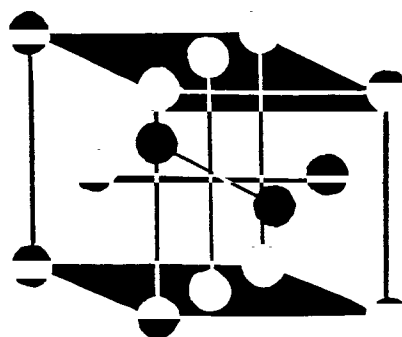
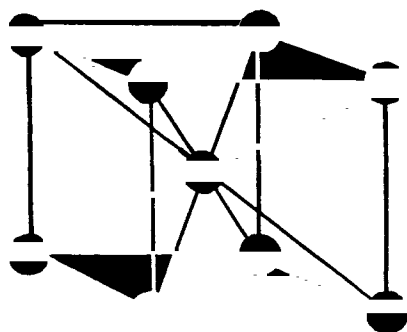
in Dr. Chikashige's work. To the modern technician, the technique described appears laborious and perhaps unnecessarily complex. However, it was built up as a result of long experience by master smiths and, with the resources available to the ancient Japanese smith, it was no doubt the best answer to the mutually contradictory requirements of a really fine blade.

Chapter VIII

EXPLANATION OF SOME TERMS USED IN DESCRIBING THE METALLURGY AND METALLOGRAPHY OF ANCIENT IRON

By I. M. ALLEN

PURE iron may be regarded as a chemical curiosity, and its existence outside the laboratory is almost unknown. Objects which we denote by the name iron are in reality alloys of this element containing from 0 to 5 per cent. of carbon and usually at least one other major constituent, e.g. manganese, nickel, or chromium. Various impurities are also present in small and varying amounts depending on the ore, its source, and methods used in refining and reduction.



FIGS. 50, 51. α - and γ -iron lattice structures as revealed by X-ray examination.

Two crystalline structures are known for iron, denoted by the letters α and γ . α -iron possesses the body-centred cubic lattice (Fig. 50) and γ -iron the face-centred cubic lattice (Fig. 51). The body-centred cubic lattice is stable up to 900° C. Above this temperature, transformation to γ -iron occurs. γ -iron is capable of holding carbon in solid solution¹ (austenite).

If a specimen of uncorroded ancient iron or steel is polished, and etched with a weak solution of nitric acid in alcohol, a characteristic structure is

¹ The random dispersion of carbon atoms in solid iron.

revealed, and this may be seen with the aid of the metallographic microscope. Each structure is characteristic for a definite range of both temperature and composition (ratio of iron to carbon).

Iron-carbon alloys containing up to 1 per cent. of carbon are shown diagrammatically in Fig. 52 (iron-carbon diagram).

Iron-Carbon Diagram

It is evident from the metallurgical reports contained in this volume, and those of Sir H. C. H. Carpenter and J. M. Robertson (1930, pp. 417-54), that progress was made in the technology of iron and steel from 1400 B.C. onward, but until the nineteenth century this knowledge remained purely empirical and was governed by a greater or lesser degree of chance. By the middle of the nineteenth century chemical analysis^{1, 2} had been introduced into the industrial study of metals. This revealed their qualitative and quantitative composition, but provided no means for checking either their macro- or microscopic structures. Towards the end of the nineteenth century vast strides were made in the microscopic examination of alloys. This type of examination consisted in studying the variation in microstructure which accompanies either an increase of the alloying element, or an increase in temperature. Each microstructure, as already stated, is characteristic for a definite range of both temperature and composition. The results of these investigations have been plotted diagrammatically to give 'thermal equilibrium diagrams' (e.g. iron-carbon diagram), and these provide a means by which a microstructure can be checked, and hence the properties of the alloy are accurately known.

Characteristic Microstructures

1. *Ferrite*. α -iron (ferrite) can contain in solid solution only up to 0.05 per cent. of carbon; it can, however, retain nickel, small amounts of manganese, phosphorus, and other elements. Its structure, which consists of a continuous network of polyhedral grains, is characteristic of pure and impure iron (Plate XI, Fig. 3). If impurities are present in considerable quantity, they may be retained undissolved in the form of mechanical inclusions; slag may often be observed flecking the ferrite grains in

¹ Simple methods for testing the purity of gold and silver are mentioned in the Bible by Zechariah (xiii. 9). Pliny (*Natural History*, Book xxxiii, 43 and 44) records the use of the touchstone for testing gold, and he also gives methods for testing the purity of silver.

² An account of the chemical methods of analysis used in the nineteenth century is given in John Percy's *Metallurgy*, 1864.

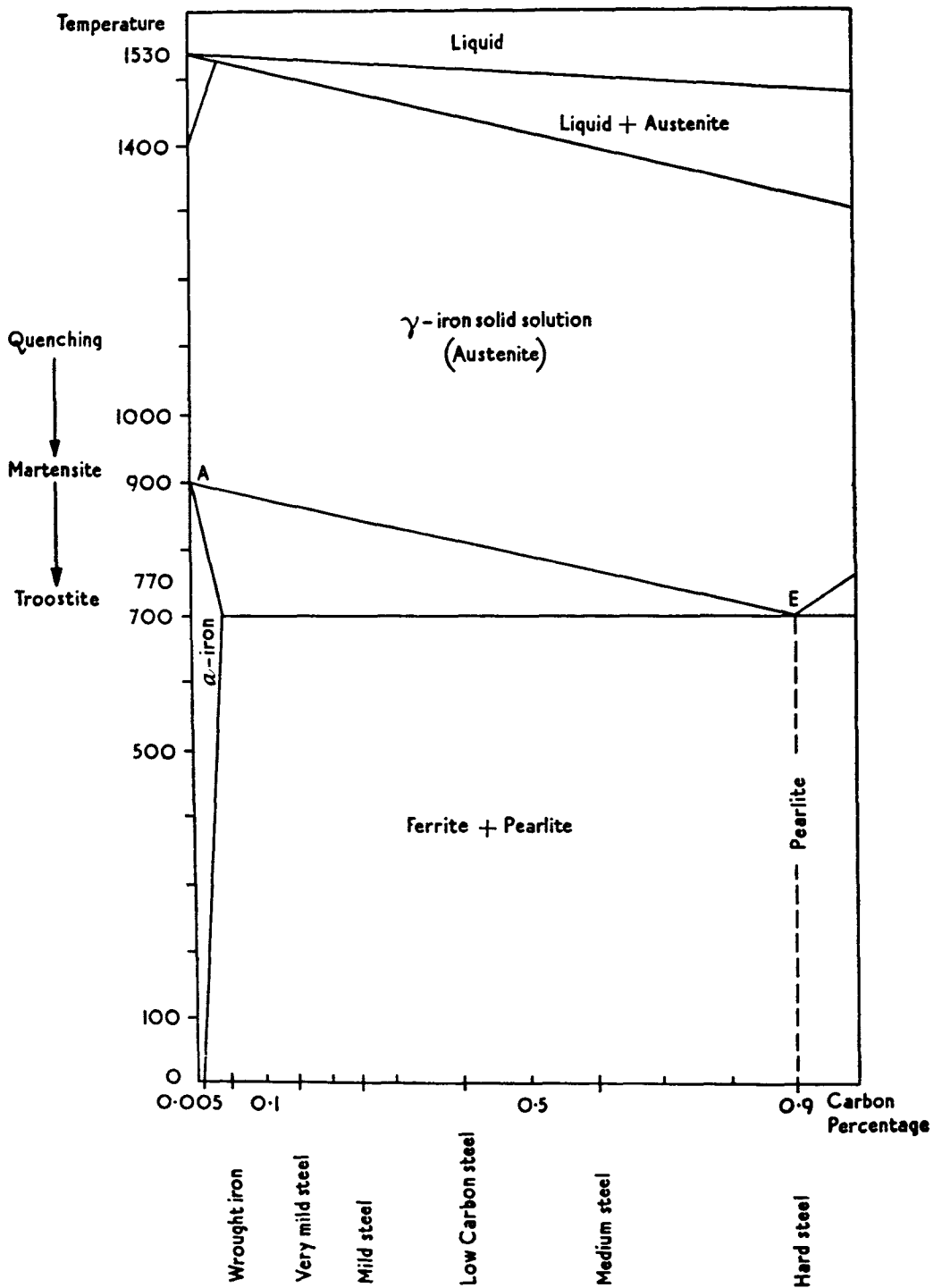


FIG. 52. The iron-carbon diagram.

this manner, and is a source of weakness, rendering the iron brittle. Should a ferrite structure be reported to the archaeologist, he may interpret it as evidence that little or no carburization has been carried out on the specimen in question. If the specimen has been subjected to severe hammering the grains may exhibit Neumann lines (Rosenhain and McMinn 1925, pp. 231-9). Most of the heavier tools and weapons of antiquity consist almost entirely of ferrite, though in some instances their cutting-edges have been hardened by carburizing.

2. *Cementite or iron carbide*. Brilliant white globular or massive free cementite occurs in low-carbon steels which have been subjected to hammering and annealed at about 680° C. (Whiteley, 1918, pp. 353-61) or have been forged in the critical ranges (700°-900° C.), particularly steels containing less than 0.15 per cent. of carbon (Plate XIV, Fig. 3). Cementite also occurs as bright laminae in pearlite.

If free cementite is reported present in the microstructure of a specimen of ancient steel containing less than 0.89 per cent. of carbon, it may be taken as evidence of forging and heat treatment.

3. *Pearlite*. Pearlite is a eutectoid¹ of ferrite and cementite containing about 0.89 per cent. of carbon. At low magnification pearlite appears as dark irregular grains, but at high magnification these can be resolved into alternate curved white and black lamellae consisting of cementite and ferrite (Plate VII, Fig. 3). Annealed steels of less than 0.89 per cent. carbon content (hypoeutectoid steels), consist of pearlite in a groundmass of ferrite. This structure is possessed by ancient carburized iron which has not been hardened or tempered.

4. *Austenite*. Austenite, as already stated, is a solution of carbon in γ -iron. It exists only at high temperatures in carbon steels and is not retained by quenching. Quenching produces martensite, and normal cooling pearlite in ferrite.

5. *Martensite*. Martensite is the hardest constituent of steel, and has the appearance of dark needles (Pl. XV, Fig. 3). Martensite is found in hardened but untempered ancient steel.

6. *Widmanstätten structure*. This structure (Pl. V, Fig. 1), which consists of large bars, needles, or plates, is produced in small forgings by overheating in the austenite range followed by fairly rapid cooling. Steel with this structure is brittle.

A similar structure exists in meteoric iron containing more than 7 per

¹ An intimate mixture of two phases (ferrite and cementite) possessing a fixed ratio of chemical composition.

cent. of nickel. The crystals of this structure are composed of three nickel-iron alloys named kamacite, taenite, and plessite. The structure is probably produced by slow-cooling and prolonged annealing (Buddhue 1948, vol. lvi, pp. 105-8).

Case Hardening

The method by which the ancient iron-smith introduced carbon into iron is known as *carburization*. This consisted of prolonged heating of iron below its melting-point but above 900° C. in intimate contact with charcoal.

Iron which has been carburized correctly will exhibit a graduation from 0.89 per cent. of carbon (pure pearlite) at the surface to a carbon-free iron core. In most specimens of antiquity the carbon content of the surface falls short of 0.89 per cent. In order to render the above treatment of value, the specimen would require hardening and tempering.

Heat Treatment of Iron and Steel

1. *Wrought iron*. Smelting iron ore with charcoal in the furnaces of antiquity before the fourteenth century A.D. usually¹ produced a type of iron which was very similar to modern wrought iron.

Wrought iron is essentially ferritic in structure, and its properties and characteristics have already been discussed under ferrite. The carbon content of ancient wrought iron was usually less than 0.1 per cent., but it was sometimes higher. It may then be classed as very mild steel and can be hardened by quenching from about 930° C.

Iron of less than 0.1 per cent. of carbon is little affected by heat treatment and quenching, although recrystallization with reduction of grain size occurs when it is heated above 900° C., due to the change in lattice structure. If the temperature is very high (1,200° C. or higher) inordinate grain growth may occur instead of reduction, and this produces brittleness. Inordinate grain growth also occurs if phosphorus is present in quantity. The influence of this element on grain growth is modified by its distribution and cold-working.

Wrought iron and very mild steel may be hardened to a certain extent by hammering, particularly between 250° C. and 425° C. (Sauveur and Lee 1925, p. 323).

Within this range of temperature, the metal is made very brittle by

¹ See, however, Chapter IV on Cast Iron, especially the section on China.

hammering, and therefore forging should be carried out at a higher temperature, preferably at about 900°C .

2. *Low-carbon steel, medium steel, and hard steel.* When the temperature of an annealed steel containing from 0.25 to 0.89 per cent. of carbon (pearlite in a groundmass of ferrite) is raised slowly to a temperature

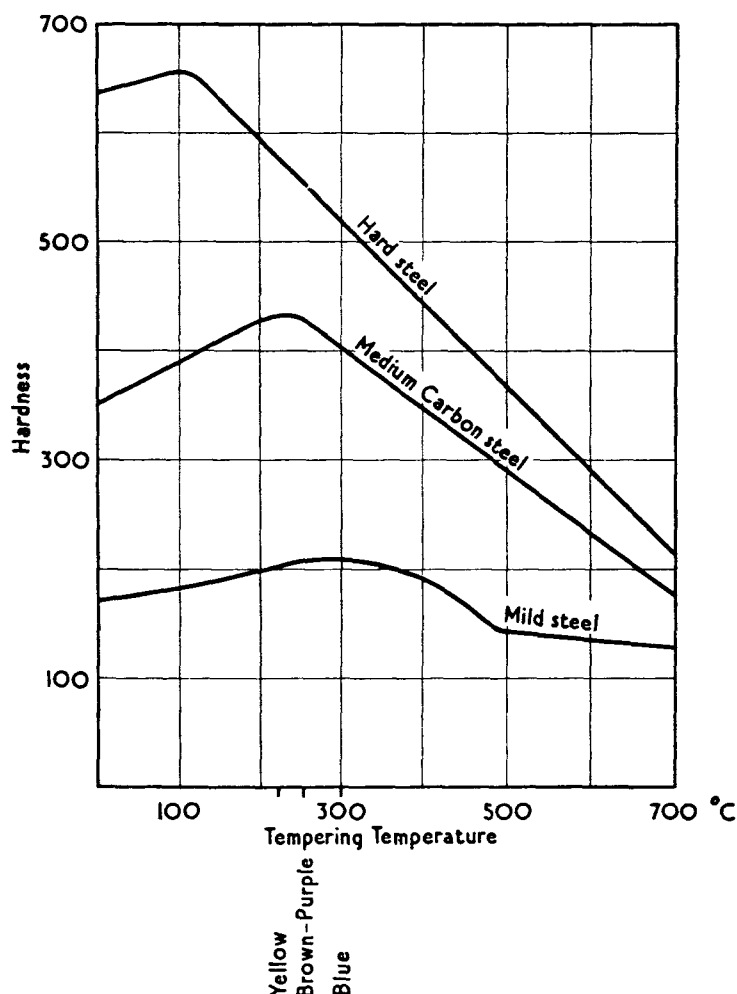


FIG. 53. Variation in hardness produced at different temperatures of tempering (modified from diagrams by Guillet and Portevin 1922).

above 900°C ., a number of changes occur. Eventually, above 900°C ., one phase will exist, namely, carbon in γ -iron solid solution (austenite). *Hardening* is then produced by quenching from about this temperature.

Quenching above the line AE (Fig. 52) will produce pure martensite, but for low carbon steels it must be drastic. Below the line AE ferrite-martensite is formed. Quenching from just below 700° C. produces the dark irresolvable constituent troostite. The tough temper variety of this constituent is found in correctly made swords and knives (Sommer 1924, 5, p. 140).

Hardness increases with increasing carbon content up to 0.89 per cent., and also with rapidity of quenching.

Tools and weapons hardened in the above manner are too brittle for use, and they therefore require a second heat treatment, *tempering*. This consists in heating to a temperature below 700° C. followed by fairly rapid cooling. This treatment causes the brittle martensite to break down into fine cementite. The treatment is adjusted by observing the oxide coloration produced on the metal at various temperatures. Fig. 53 shows the variation of hardness produced at different temperatures of tempering.

Chapter IX

AN ESKIMO KNIFE COLLECTED BY SIR JOHN ROSS

By I. M. ALLEN

AN Eskimo knife collected on the 13th of August 1818 from Prince Regent's Bay, N. Greenland, by Captain John Ross, R.N., and illustrated on Plate 13, opposite page 102 in his *A Voyage of Discovery*, 1819, has been chosen to show how meteoric iron was used. This specimen (see Fig. 2) is not only of historic interest, but also provides an example of an iron weapon made with stone tools. When the specimen was compared with the illustration on Plate 13 it was seen that two sections of iron were missing, and we have since concluded that these were probably used by Dr. Wollaston for the nickel determination given in appendix No. III, LXXXIX of *A Voyage of Discovery*. This conclusion is based on pages 95-117 of the above work, from which it is evident that, although John Ross earnestly requested the Eskimo he encountered to bring him samples of the native iron with which they edged their weapons, there is no reference to their having fulfilled this request, though on several occasions they promised to do so (see pp. 104, 105, 111, and 112). There is also mention in *The Journal of Science and the Arts*, 1819, vol. ii, p. 369, of iron samples taken from implements collected by Captain Ross in the same area for nickel determination.

The following extract from J. Ross's *A Voyage of Discovery* (p. 104) describes the occurrence and working of native iron. 'He (Meigack) was now interrogated respecting the iron with which his knife was edged' (the knife is about 1 foot long and made of walrus ivory edged with meteoric iron) 'and informed us that it was found in the mountain before mentioned; that it was in several large masses, of which one in particular, which was harder than the rest, was a part of the mountain, that the others were in large pieces above ground, and not of so hard a nature; that they cut it off with a hard stone, and then beat it flat into pieces of the size of a sixpence, but of an oval shape. As the place where this metal was found, which is called Sowallick, was at least twenty-five miles distant, and the weather very unsettled, I could not venture to send a party to examine

it, being uncertain how soon we might be forced from our present situation.'

A metallographic examination of the nickel-iron (Fig. 54, *f*, *g*.) revealed that the metal had been severely distorted by mechanical working, and the presence of Neumann lines indicate that it had not been annealed.

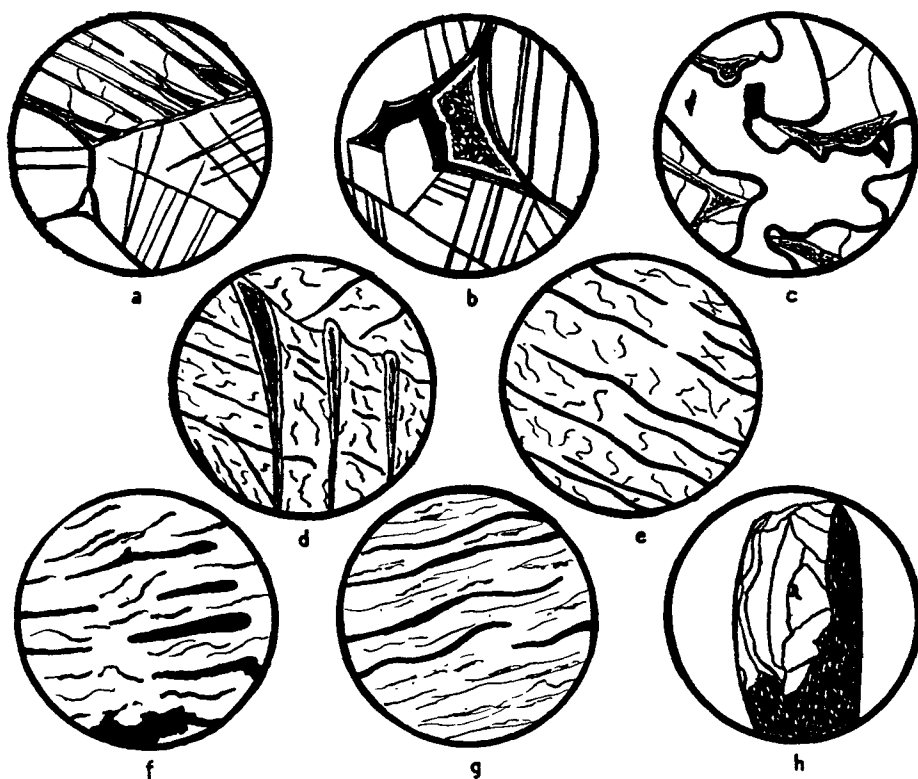


FIG. 54. Structures of meteoric iron before and after cold-forging.

Comparatively few inclusions were found in the section examined. The macrostructure (Fig. 54, *h*.) exhibited considerable cracking, and it is evident that the metal is now very friable. Its hardness averaged 227 Brinell.

Chemical analysis of the metal revealed that it consists of 88.0 per cent. of iron, 11.83 per cent. of nickel, and traces of cobalt and copper. The high nickel content proves it to be of meteoric origin, since this element rarely exceeds 2.5 per cent. in terrestrial iron. Terrestrial iron usually contains a high percentage of carbon (1.0–3.5 per cent.), and its structure is therefore either that of a high-carbon nickel steel or pig iron (Carpén-

ter 1935, p. 153; Löfquist and Benedicks 1941, pp. 1-96). The present writer examined a specimen of terrestrial iron from Blaafeld, Ovifak, and found it to consist mainly of massive cementite and fine globular pearlite with inclusions of troilite.

Cold-forging of meteoric iron

Fig. 55*a* shows the macrostructure of a small billet of meteoric iron from which a small knife (Fig. 55*b*) was successfully cold-forged. The forging was made with a 1 lb. 4 oz. hammer. During the initial hammering, a small part of the billet broke off. The cause of this fracture appeared to be due to the presence of a large cohenite grain (Fig. 54*c*). After this fracture, the remaining portion was forged to its present shape without further mishap. Fig. 54*a*, *b* show the microstructure of the metal before forging, and Fig. 54*d*, *e* after cold-forging. The average Brinell hardness before forging was 229, and after, 233.

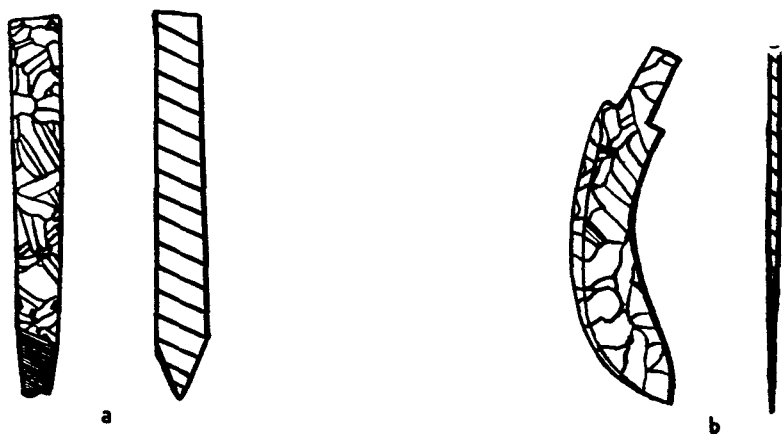


FIG. 55. Macrostructure of billet of meteoric iron before and after cold-forging. Scale 1/1.

Chapter X

A METALLOGRAPHIC AND METALLURGICAL EXAMINATION OF SPECIMENS SELECTED BY THE PITT RIVERS MUSEUM¹

By Courtesy of

THE DIRECTOR OF RESEARCH AND TECHNICAL DEVELOPMENT OF
MESSRS. STEWARTS AND LLOYDS

1. 1953.6.1. ASSYRIA, NIMRUD. TWO PIECES OF IRON FROM TRIPODS, LATE EIGHTH CENTURY B.C. Plate I, Fig. 2. PITT RIVERS MUSEUM.

Weight 92.62 grams.

Examination of this sample shows that it has been completely converted to iron hydroxide. Examination of a section shows a piled structure which would indicate that the tripod iron was made from piled wrought material. Analysis of the sample has not been carried out as there is no metallic portion left.

2. 1953.1.32. SYRIA, DEVE HÜYÜK. BROKEN SPEAR-HEAD WITH MID-RIB, SOCKETED, WITH BROKEN-OFF PIECE OF SOCKET. 600-500 B.C. PITT RIVERS MUSEUM.

Length $8\frac{1}{2}$ in.

Total weight 107.0 grams.

Examination shows that this spear-head is of forged carburized steel made from reduced sponge iron. It has been forged from a large number of plates, the majority of which have been surface carburized during heating for forging.

The spear-head shows a pronounced piled water-marked structure, indicating a high degree of skill in the welding and forging operations.

The structure and hardness do not reveal any indication of hardening and tempering treatment.

A drawing of the spear-head is shown in Fig. 56, No. 6.

Before the examination commenced the spear-head was X-rayed to show which portions were still in the metallic condition.

¹ With Plates I, Fig. 2, to XVI and EXPLANATION OF THE PLATES, pp. 202-5, also Figs. 56 and 57 in the text.

Plate II, Fig. 1, is a print from a radiograph. It shows that corrosion has eaten away the metallic portions in the dark patchy areas, leaving the heavy midrib and some of the blade and socket still in the metallic state.

Careful machining, grinding, and polishing of the spear-head on one side reveals that the metal left in the blade is exceedingly thin, much of it having been converted to oxide. It was arranged that the material removed for analysis would be taken from one side, leaving the other face of the spear-head undamaged. Extensive corrosion, particularly at the socket end, made the sampling very difficult; some of the corroded portions fell away on removing the metal for analysis.

The analysis of the spear-head (see p. 182) shows that it has been made from steel with an average carbon content of 0.18 per cent. The low phosphorus and sulphur contents show the ore used for producing the steel was of pure grade. The nickel content of 0.32 per cent. is rather unusual in an implement of this type.

Macro- and microscopical examination have been carried out on the polished section, revealing a layered structure, Plate II, Fig. 2. Examination of the socket end, which was detached, shows the remains of a wooden shaft still in place. At this position, despite the heavier section, the steel is almost completely corroded away. The structure of the corrosion products, however, retains the layered pattern of the original steel interleaved in places with copper filaments, Plate IV, Fig. 2.

The socket portion is continuous with the blade. It has been formed by building up a tapered tubular shape and brazing and forging together with impure copper, Fig. 44. The copper is relatively untouched by corrosion, being more noble than the steel. The presence of copper at the socket end may account for the more extensive corrosion at this position.

The photomacrograph, Plate III, Fig. 1, and the photomicrograph, Plate III, Fig. 2, show the highly contorted layered structure, indicating that the metal used for forging the spear-head was built up from a large number of layers of iron plates resulting in a highly developed water-marked pattern somewhat similar to 'damascene' steel blades produced from cast steel.

Reduced sponge iron was forged into plates, piled into a block, and repeatedly forged, resulting in the water-marked structure. It is estimated that the spear-head contains about 50 layers. The sponge iron contains some entangled cinder and gangue which were not expelled during forging. In some places the fire welding of the various laminations has not

been complete, and particularly towards the shaft end extensive corrosion has penetrated into the layered structure.

Plate IV, Figs. 1 and 3, show high-power views taken from the same field as Plate III, Figs. 1 and 2.

The dark carbon-bearing areas at the junction of each layer, Plate IV, Fig. 1 ($\times 200$), show that the carbon content is in places as high as 0.6 per cent., indicating that the heating for forge welding was carried out under carburizing conditions, possibly on a charcoal fire, giving a localized surficial increase in the carbon content.

The structure at a magnification of $\times 1000$ is shown in Plate IV, Fig. 3; this is typical of material which has been forged on a falling temperature and has then been left to cool very slowly from about 450°C. , possibly in hot ashes or at the edge of the smith's fire.

The grain size varies from 200 to 25,000 grains/sq. mm. This irregularity in grain size confirms that the final forging was carried on to quite a low temperature.

The Vickers diamond hardness varies from 108 Vickers in the low carbon zones to as high as 153 Vickers in the higher carbon bands. These hardness figures are typical of a modern mild steel.

There is no indication of the spear-head having been hardened and tempered.

Analysis:

Phosphorus	. 0.021 per cent.	Nitrogen	. . 0.006 per cent.
Sulphur	. . 0.014 "	Copper	. . 0.01 "
Silicon	. . 0.10 "	Nickel	. . 0.32 "
Manganese	. . 0.04 "	Arsenic	. . 0.024 "
Carbon	. . 0.18 "	Vanadium	. . 0.01 "

3. LACHISH IRON PICK. AREA DESTROYED *c.* 588 B.C. (LACHISH, iii, Pl. 61. 3).

Examination of this pick shows it is made from a very pure base wrought iron which has been carburized prior to piling and forging.

The analysis is:

Carbon	. . 0.196 per cent.	Chromium	. . Trace
Manganese	. . 0.013 "	Molybdenum	. . 0.010 per cent.
Silicon	. . 0.010 "	Vanadium	. . Nil
Sulphur	. . 0.005 "	Copper	. . 0.004 per cent.
Phosphorus	. . 0.013 "	Arsenic	. . 0.006 "
Nickel	. . 0.008 "	Nitrogen	. . 0.0035 "

SPECIMENS SELECTED BY THE PITT RIVERS MUSEUM

An iron with such a pure base and such a low arsenic content would have been produced from a pure haematite or magnetite ore.

A general view of the pick is shown in Fig. 57. A photomicrograph, Plate V, Fig. 1, of a prepared area close to the point shows a very coarse Widmanstätten structure, indicating that the pick point was quenched from a very high temperature (over 1,000° C.). In the same field there are numerous slag filaments along one of the piling planes.

The hardness varies from 136 to 183 Vickers.

4. SAMPLE FROM EDGE OF A SOCKETED AXE, MAGDALENENBERG BEI ST. MAREIN, JUGOSLAVIEN, TUMULUS II, GRAB I UND 2, HALLSTATT PERIOD, SIXTH CENTURY B.C. PRÄHISTORISCHE SAMMLUNG IM NATURHISTORISCHEN MUSEUM, WIEN, NO. 22006.

A drawing of the axe appears in Fig. 57, No. 3.

The analysis of the sample (see Plate V, Fig. 2) shows a rather high carbon wrought iron with numerous entrapped slag filaments. There is no sign of hardening.

Grain size, 4,000 to 1,000 gr./sq. mm.

Vickers hardness, 149 to 165.

Analysis:

Carbon . . .	0.10 per cent.	Chromium . . .	Not indicated
Manganese . . .	0.02 „	Molybdenum . . .	„
Nickel . . .	0.01 „	Vanadium . . .	„
Copper . . .	0.020 „		

5. SMALL SAMPLE FROM BLADE OF A LANCE-HEAD, HALLSTATT, GRÄBERFELD, GRAB 783, HALLSTATT PERIOD, SIXTH CENTURY B.C. VIENNA MUSEUM AS ABOVE, NO. 22016.

A drawing of the lance-head appears in Fig. 57, No. 2.

The analysis of the sample (Plate V, Fig. 3) shows the blade to be of pure wrought iron with numerous entrapped slag filaments. There is no sign of hardening.

Grain size, 1,000 to 260 gr./sq. mm.

Hardness, 145 to 154 Vickers.

Analysis:

Carbon . . .	Less than 0.04 per cent.	Copper . . .	0.12 per cent.
Manganese . . .	0.06 per cent.	Vanadium . . .	Trace
Nickel . . .	0.09 „	Chromium . . .	Not indicated
		Molybdenum . . .	„

6. 1953.1.33. JUGOSLAVIA, VAČE. SPEAR-HEAD WITH SMALL POINT AND LONG SOCKET, FIFTH CENTURY B.C. PITT RIVERS MUSEUM.

Fig. 56, No. 1, shows a drawing of the spear-head. Extensive corrosive attack has occurred, and in places the material in the region of the shaft socket is completely converted to iron hydroxide.

A portion extending for $3\frac{1}{4}$ inches back from the point has been sectioned, polished, and etched to study the microstructure. Millings from this section have been analysed with the following results:

Silicon . . .	Trace	Vanadium . . .	Nil
Manganese . . .	0.006 per cent.	Phosphorus . . .	0.050 per cent.
Copper . . .	0.01 „	Sulphur . . .	0.012 „
Nickel . . .	0.005 „	Carbon . . .	0.319 „
Chromium. . .	Trace	Arsenic . . .	0.009 „
Molybdenum . .	Nil	Nitrogen . . .	0.007 „

A photomicrograph of this portion at a magnification of about $1\frac{1}{2}$ is shown in Plate VI, Fig. 1.

The examination shows that the spear-head has been forged from wrought iron with a very variable carbon content. In the lower portion of Plate VI, Fig. 1, the carbon content exceeds 0.6 per cent. locally, possibly by carbon pick-up from a charcoal fire, whereas in the upper portion the carbon content is less than 0.1 per cent.

The examination shows that the point has been formed by rolling over a faggot of wrought iron in the form of a forge-welded tubular section, which has been completely collapsed at one end to form the point, but still retains the tapered tubular form at the socket portion. The line of the welding can be seen extending from the point to the open end of the socket.

The grain size of the head varies from 20 to 15,000 gr./sq. mm., and the Vickers hardness varies from 103 to 134.

The section shows numerous streamers of non-metallic cinder which have not been expelled during the welding and forging operation. In the high-carbon areas (lower portion, Plate VI, Figs. 1, 2), the heating for forging has caused local burning in the high-carbon portion. This has resulted in numerous fissures shown in the lower portion of Fig. 2. A photomicrograph near to the weld line close to the point of the spear-head is shown in Plate VI, Fig. 3, and at a higher magnification in Plate VII, Fig. 1. At this position the structure resembles that of a normalized steel. At other positions close to the point, and on the flanks of the spear-

head, the carbon content is more typical of wrought iron. In places extensive areas of entrapped cinder are still evident (Plate VII, Fig. 2.)

The examination shows that no attempt has been made to quench and temper the spear-head. The higher carbon pearlitic areas, shown in Plate VII, Fig. 3, are typical of a steel which has been slowly cooled after forging.

7. LA TÈNE SWORD FROM HISTORISCHES MUSEUM, BASEL. SWORD NO. 1947.639.

A general view of the blade is shown in Fig. 57, No. 1.

Small areas have been prepared for examination at approximately the mid length of the blade and at the point. Microscopical examination shows that the material is very low-carbon wrought iron which is remarkably free from entrapped slag.

The grain size on the central rib is coarse and variable, in places the grains are very large, approximately 2 gr./sq. mm. (Plate VIII, Figs. 1, 2). The hardness near the central rib is 161 Vickers. At one position there is a small area which has a carbon content of about 0.6 per cent., possibly resulting from localized carburizing by contact with charcoal during the heating for forging.

At the cutting-edge the grain size is much finer, and the carbon content at this position is slightly higher than at the central rib. There are a few grains containing nitride needles.

In places at the cutting-edge the grains are distorted and are heavily veined, which indicates that the blade is in the as-forged condition and that the forging was carried out until the edge of the blade fell to a temperature of about 450° C., where complete recrystallization after forging would fail to take place (Plate VIII, Fig. 3). At the cutting-edge the grain size, although variable, is in places as fine as 2,000 gr./sq. mm.; the Vickers hardness is 190.

In patches near the central rib there are areas containing pronounced Neumann bands (Plate VIII, Fig. 2), indicating that the blade was hammered with very sharp blows in the cold condition. These Neumann bands may, of course, have been formed by straightening the blade by hammering cold at some time after use.

The analysis is:

Silicon	. Not indicated	Copper	. . Trace
Manganese	. Not indicated	Nickel	. . 0.05 per cent.
Carbon	. 0.1 to 0.04 per cent.	Chromium	. Not indicated

A METALLOGRAPHIC AND METALLURGICAL EXAMINATION OF

Grain size approximately 2 gr./sq. mm. to 2,000 gr./sq. mm.

Vickers hardness 161 to 190.

8. LA TÈNE SWORD FROM HISTORISCHES MUSEUM, BASEL. SWORD NO. 1947.640.

A general view of this blade is shown in Fig. 57, No. 10.

A small area has been prepared for microscopical examination about the centre of the length and at the point. The examination shows that the blade is a good quality wrought iron with a large number of piled layers (Plate IX, Fig. 1). Near the cutting-edge the layers are highly contorted due to hammering. The junctions of the layers are free from large particles of entrapped slag.

There is a variable carbon content from the edge to the central rib. Near the central rib the carbon content is about 0.15 per cent., and the ferrite grain size is approximately 1,000 gr./sq. mm.; a typical area is illustrated in Plate IX, Fig. 2. Close to the cutting-edge the structure becomes very coarse and acicular, and the carbon content rises to approximately 0.5 per cent. This coarse structure indicates that the final forging temperature was about 1,000° C.

During the final forging the central rib of the blade has received more hot forging than the cutting-edge; this has resulted in a much finer grain structure in the central rib, Plate IX, Fig. 2.

Examination of an area prepared close to the point of the blade shows the same coarse 0.5 per cent. carbon structure very similar to Plate X.

There is no evidence of hardening by quenching. The blade is in the as-forged condition, and the carbon content of the cutting-edge is a good deal higher than at the central rib and changes across the blade. This indicates that the edge of the blade was carburized, or that the edge portion had a higher carbon content in the original forged faggot used to make the blade.

The analysis of the blade is:

Silicon	. 0.02 per cent.	Copper	. . .	Trace
Manganese	. Not indicated	Nickel	. . .	0.04 per cent.
Carbon	. 0.15 to 0.5 per cent.	Chromium	. . .	Not indicated

The grain size varies from 1,000 gr./sq. mm. in the central rib to approximately 35 gr./sq. mm. at the cutting-edge.

The Vickers hardness varies from 161 at the low-carbon central rib to 286 in the coarse higher-carbon zone at the cutting-edge.

9. OXYRHYNCHUS, EGYPT. TANGED KNIFE 6.9 IN. LONG. ROMAN. PITT RIVERS MUSEUM.

Weight 37.2 grams.

A drawing of the knife is shown in Fig. 56, No. 5. When received the portion of the blade at the upper side of the photograph was approximately $\frac{1}{16}$ -inch thick, while the edge at the bottom portion of the blade tapered off to a few thousandths of an inch in thickness; the blade and edge were heavily corroded and pitted; this made sectioning and examination exceedingly difficult. It was necessary to mount the whole of the blade in an air-setting plastic to allow the sectioning and preparation without distorting the edge.

A longitudinal section of the blade after grinding, polishing, and etching is shown in Plate XI, Fig. 1. The blade has been built up from a large number of faggots of wrought iron which have been forge-welded in piles leaving a blade with a wavy-flow pattern. The flow pattern developed by etching is highly contorted; there are numerous slag filaments at the junction of the layers which have not been expelled during the welding and forging (Plate XI, Fig. 2).

Due to the fragility of the blade, it was not possible to remove material for analysis without destroying the specimen, but portions have been arched and sparked to allow a spectrographic examination to be made, with the following results:

Copper	.	.	0.01 per cent.	Manganese	.	.	.	Nil
Tin	.	.	0.002 "	Nickel	.	.	.	"
Chromium	.	.	Nil	Vanadium	.	.	.	"
Molybdenum	.	.	"	Titanium	.	.	.	"
Silicon	.	.	"					

The material is an exceedingly pure base wrought iron with a very low general-carbon content. Certain layers of the blade, however, are higher in carbon content than others. This is possibly due to carbon pick-up from a charcoal fire by certain faggots during the repeated forging and welding operations.

Close microscopical examination along the edge of the blade shows that no attempt has been made to carburize or harden and temper the material by quenching and tempering. It is observed, however, that the ferrite grains contain numerous Neumann bands which occur on the slip planes of the grains. These Neumann bands have been produced by hammering the blade cold after the hot forging, possibly during the finishing stages of its preparation (Plate XI, Fig. 3).

A METALLOGRAPHIC AND METALLURGICAL EXAMINATION OF

The ferrite grain size is very variable, counts varying from 20 gr./sq. mm. to 20,000 gr./sq. mm. This variation in grain size is typical of wrought iron which has been hot-forged over a wide temperature range until the blade was cold.

The Vickers hardness of the blade varies from 113 to 120 Vickers which, although harder than normal wrought iron, is explained by the cold hammering. This hardness is typical of a modern low-carbon mild steel.

10. ROMAN SAW, OXYRRHYNCHUS. PITT RIVERS MUSEUM.

A drawing appears in Fig. 57, No. 4.

Examination of a portion of the blade close to the teeth shows this saw has been made from piled wrought iron. The carbon content is about 0.1 per cent. See Plate XII, Fig. 1.

No analysis has been made as this would have necessitated destroying the specimen.

The grain size varies from 1,000 to 2,000 gr./sq. mm.

The Vickers hardness of the teeth varies from 127 to 140.

The microstructure is typical of a low-carbon steel which has been hot-worked until the temperature has fallen below a red heat. There is no indication that the blade has been quenched and tempered.

This saw would not remain sharp for very long when cutting even soft wood.

11. HARAGEH, EGYPT. ROMAN RING AND TWEEZERS, AND RING AND STAPLE, FROM NEWBURY MUSEUM.

Drawings appear in Fig. 57, Nos. 8, 9.

The tweezers (No. 8) have a ring made from wrought iron with a carbon content of approximately 0.15 per cent. The grain size varies from 20 to 2,000 gr./sq. mm., and the Vickers hardness varies from 145 to 165.

The tweezer blades are also made from a wrought iron which has been carburized (approx. 0.15 per cent.). The ends of the blades have been hot-worked on a falling temperature. This has resulted in a mixed grain size with the carbides highly agglomerated (Plate XII, Fig. 2). Some Neumann bands were observed near the end of the tweezers, showing that they had been hammered cold.

No analysis has been made of this item as it would have necessitated destroying the specimen.

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The tweezer blades have a grain size varying from 140 to 8,000 gr./sq. mm. The Vickers hardness varies from 176 to 237.

Examination of the ring and staple shown in Fig. 57, No. 9, shows that the ring has been made from wrought iron with a very variable grain size, 20 to 2,000 gr./sq. mm. The Vickers hardness varies from 145 to 154. The carbon content is approximately 0.1 per cent.

The staple portion has a carbon content of about 0.25 per cent. The structure shows that the staple has been made from wrought iron as it shows piling with entrapped slag. The pointed ends of the staple have been hammered on a falling temperature; there is a considerable amount of cold work in the ends, the hardness varying from 189 to 336 Vickers.

Typical structures of the staple ends are shown in Plate XII, Figs. 3 and 4.

No analysis has been made of this item as it would have necessitated destroying the specimen.

12. 1953.1.34. FRILFORD, BERKSHIRE, ROMAN TANGED KNIFE, THIRD TO FOURTH CENTURY A.D. PITT RIVERS MUSEUM.

A drawing of this knife appears in Fig. 56, No. 4.

Plate XIII, Fig. 1, shows a print from an X-ray negative. Close examination of this negative shows a fibrous structure typical of wrought iron. The only solid metallic portion is at the junction of the tanged end at the beginning of the blade.

Plate XIII, Fig. 2, shows a transverse section from the end, displaying a piled wrought structure. Only small portions of the wrought material remain. The bulk of the blade has been converted to iron hydroxide.

A photomicrograph of the uncorroded portion shows the coarse ferritic grain size typical of low-carbon wrought iron (Plate XIII, Fig. 3).

13. SILCHESTER ROMAN AXE, FOURTH CENTURY A.D., READING MUSEUM.

Weight 734 grams.

A drawing of the axe-head is shown in Fig. 57, No. 7.

The whole surface is covered with a heavy layer of very hard rust.

Drillings for analysis have been taken from the heavy portion of the blade close to the socket. Only one hole has been drilled to avoid spoiling the specimen.

The analysis is:

Carbon	.	.	0.319 per cent.	Chromium	.	.	Nil
Manganese	.	.	0.013 „	Molybdenum	.	.	0.020 per cent.

A METALLOGRAPHIC AND METALLURGICAL EXAMINATION OF

Silicon . . .	Trace	Vanadium . . .	Nil
Sulphur . . .	0.007 per cent.	Copper . . .	0.015 per cent.
Phosphorus . . .	0.061 „	Arsenic . . .	0.071 „
Nickel . . .	0.033 „	Nitrogen . . .	0.0065 „

This is a pure base material which has been carburized. The arsenic content is typical of irons made from European siderite ores.

Metallographic examination has been made on a small prepared area running up to the edge on one face of the axe.

A photomicrograph of this area, Plate XIII, Fig. 4, shows the blade has been made from a large number of layers of piled carburized wrought iron, which have been welded together prior to forging the axe. The general orientation of the layers is roughly parallel to the edge of the axe, but they have a highly contorted outline as a result of repeated forging; they contain elongated slag filaments typical of those shown in Plate XIV, Fig. 1. The carbon content at the welds at the junction of each layer is in places below 0.05 per cent., and the ferrite grain size is in places very coarse. The dark central portions (Plate XIII, Fig. 4) of the layers have a carbon content of more than 0.6 per cent.

A typical structure near the centre of the layers is shown at a higher magnification in Plate XIV, Figs. 1, 2. The grain size (6,500 to 8,000 gr./sq. mm.) is very fine, with a ferritic background and a heavy network cellular carbide structure together with spheroidized carbide particles. This structure is typical of a medium-carbon steel, which has been forged on a falling temperature until it reaches about 700° C., and is then given a prolonged annealing in the range 650° C. to 700° C., where the carbides become agglomerated and spheroidized.

The hardness near the edge of the blade varies from 118 to 210 Vickers.

14. SAXON AXE, READING MUSEUM.

A drawing of the axe head is shown in Fig. 57, No. 5. A large piece has broken away from the upper portion of the edge.

The specimen is coated with a very heavy layer of hard rust.

Drillings have been taken from the heavy portion of the section close to the socket.

The analysis is:

Carbon . . .	0.23 per cent.	Chromium . . .	Not indicated
Manganese . . .	0.01 „	Molybdenum . . .	„
Silicon . . .	Not indicated	Vanadium . . .	Trace

SPECIMENS SELECTED BY THE PITT RIVERS MUSEUM

Sulphur . . .	0.008 per cent.	Copper . . .	0.01 per cent.
Phosphorus . . .	0.130 „	Arsenic . . .	0.049 „
Nickel . . .	0.02 „	Nitrogen . . .	0.005 „

Grain size 65 to 500 gr./sq. mm.

Hardness of edge 154 to 165 Vickers.

Microscopical examination on the top of the blade near the chipped portion shows a piled structure with layers of varying carbon content.

The structure is coarse and acicular, the carbide areas are spheroidized; this indicates that the axe was cooled from a forging temperature (over 1,000° C.) and was reheated to about 700° C. for a period which allowed the carbides to spheroidize.

The structure of a prepared area near the edge showed numerous Neumann bands in a practically carbonless ferritic background (Plate XIV, Fig. 4). The extremely low carbon content (below 0.04 per cent.) close to the edge is the result of prolonged heating which has decarburized the thin portion of the cutting-edge. The presence of the Neumann bands in the ferrite grains shows the edge has been heavily hammered cold.

There is no sign of quenching and tempering, and the edge of such an axe would quickly become blunt. The high phosphorus content would also make the edge brittle.

15. DANISH BATTLE-AXE. 895 OR 896 A.D. BED OF RIVER LEA NEAR STRATFORD, ESSEX. NEWBURY MUSEUM, No. 1898-5, NOW PITT RIVERS MUSEUM, 1954.11.11.

Weight 691 grams.

See Plate XV, Figs. 1-4, and Fig. 56, No. 3.

Examination shows that this Danish battle-axe has been made from low-carbon sponge iron which contains a small quantity of entangled cinder not expelled during the forging.

The analysis is:

Silicon . . .	0.04 per cent.	Molybdenum . . .	Nil
Manganese . . .	0.01 „	Vanadium . . .	„
Copper . . .	0.01 „	Phosphorus . . .	0.445 per cent.
Nickel . . .	0.07 „	Sulphur . . .	0.011 „
Chromium . . .	Nil	Carbon . . .	0.049 „
Magnesium . . .	0.005 „	Arsenic . . .	0.042 „
Aluminium . . .	0.04 „	Nitrogen . . .	0.0085 „

The blade has a highly contorted layered structure, indicating that the iron has been piled and repeatedly forged from faggots of sponge iron; the fibre or grain flow is parallel to the cutting-edge.

The shaft socket has been formed by lapping over a tongue from the forging and forge welding this to one side of the blade.

The analysis and microscopical examination of the body of the blade show that the carbon content is typical of wrought iron; the relatively high body hardness of 160 to 170 Vickers is due to the high phosphorus content. The blade, and particularly the edge which is hardened, would tend to be somewhat brittle with such a high phosphorus content.

The immediate cutting-edge of the blade has been locally carburized by heating the edge in contact with carbonaceous material. The edge has been quenched and has a surface hardness varying between 350 and 450 Vickers.

The grain size of the main body of the blade is very variable, counts vary from 250 gr./sq. mm. to 1,500 gr./sq. mm. The structure is banded, and in places highly contorted, showing a marked wavy appearance typical of material which has been repeatedly forged.

16. 1953.1.35. WOODEATON, OXON. TANGED AND SOCKETED ARROW-HEAD, MEDIAEVAL. PITT RIVERS MUSEUM.

Length $2\frac{1}{2}$ in.

Total weight 13.7 grams.

See Plate XVI, Figs. 1-4, and Fig. 56, No. 2.

Analysis:

Silicon . . .	Trace	Molybdenum . . .	Nil
Manganese . . .	„	Vanadium . . .	„
Copper . . .	0.01 per cent.	Phosphorus . . .	..
Nickel . . .	0.004 „	Sulphur . . .	..
Chromium . . .	Trace	Carbon . . .	0.050 per cent.
Magnesium . . .	0.003 per cent.	Arsenic . . .	0.008 „
Aluminium . . .	0.01 „	N ₂ . . .	..

The arrow-head is made from wrought iron. It has a very variable grain size. The microstructure indicates that no attempt has been made to harden the point.

Grain size 20 to 25,000 gr./sq. mm.

Hardness 115 to 155 Vickers.

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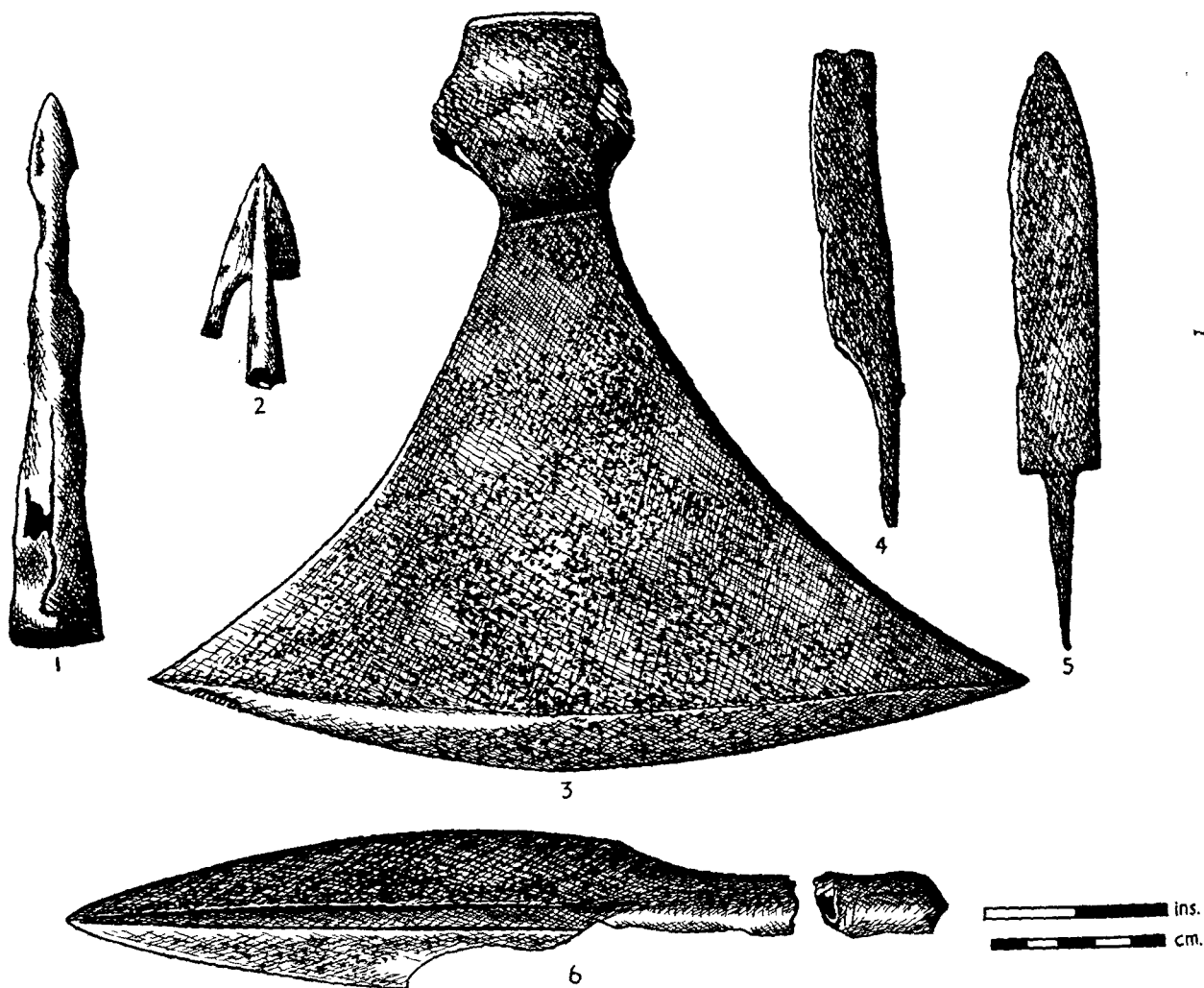
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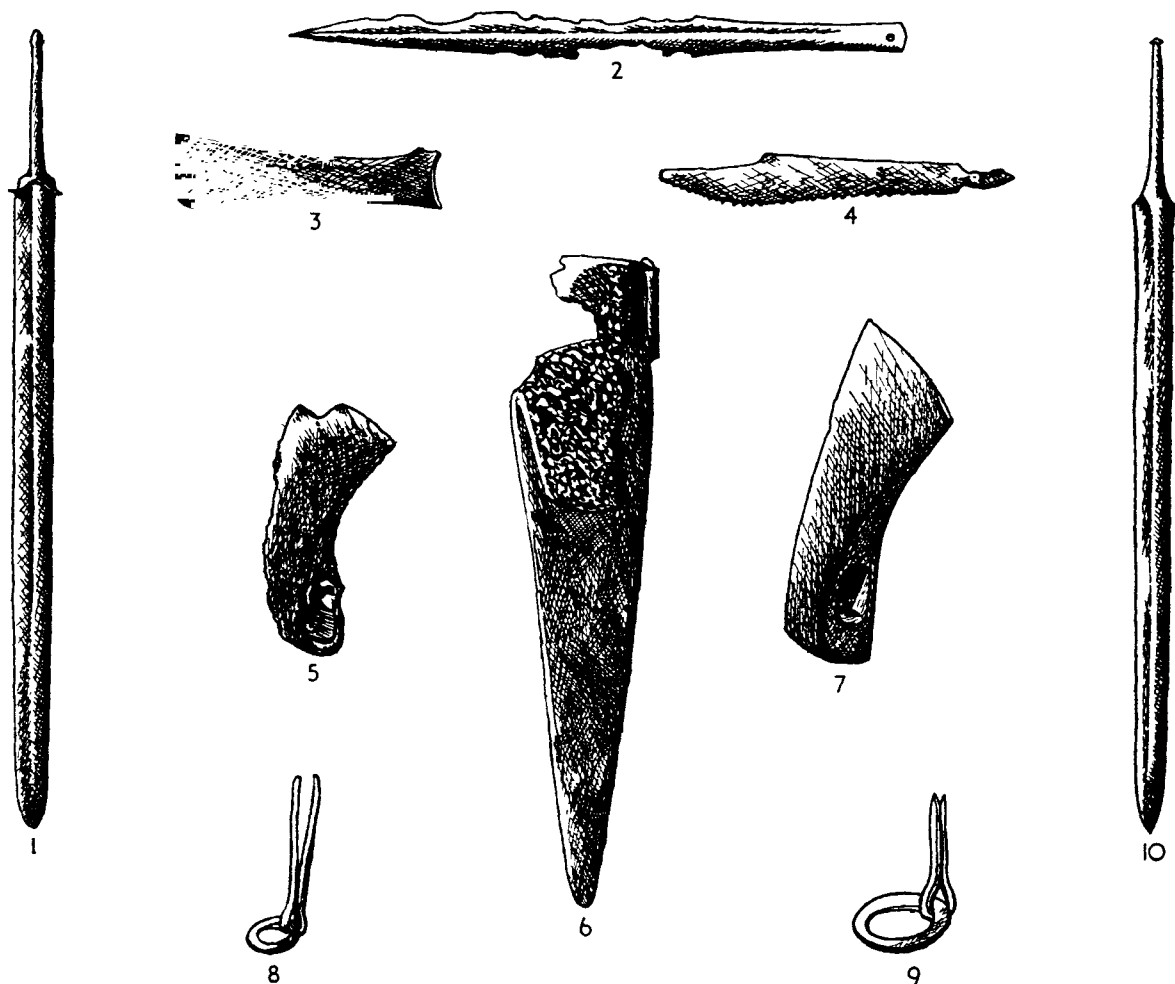
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IRON OBJECTS ANALYSED FOR THE PITT RIVERS MUSEUM

FIG. 56. 1. Jugoslavia, Vače, spear-head, 5th century B.C. 2. Mediaeval arrow-head, Woodeaton, Oxon. 3. Danish battle-axe, 895 or 896 A.D., bed of River Lea near Stratford, Essex. 4. Tanged knife, Roman villa, Frilford, Berks., 3rd-4th century A.D. 5. Tanged Roman knife, Oxyrhynchus, Egypt. 6. Syria, Deve Hüyük, spear-head, 600-500 B.C.



IRON OBJECTS ANALYSED FOR THE PITT RIVERS MUSEUM

FIG. 57. 1 and 10. Two swords from La Tène, *c.* 50 B.C. (87 and 90 cm.). 2. Hallstatt, Austria, lance-head, 6th century B.C. (44 cm.). 3. Magdalenenberg, Jugoslavia, socketed axe, 6th century B.C. (20 cm.). 4. Roman saw, Oxyrhynchus, Egypt (12 cm.). 5. Saxon axe, Reading (13.5 cm.). 6. Pick, Lachish, from area destroyed *c.* 588 B.C. (24 cm.). 7. Roman axe, Silchester, Hants, 4th century A.D. (18 cm.). 8, 9. Roman tweezers and staple, Harageh, Egypt (9 cm. and 7.5 cm.).

EXPLANATION OF THE PLATES

PLATE I

1. Photomicrographs of the surface of a sword (France-Lanord 1949). $\times 40$. *a, c.* Zones of carburized iron (mild steel) in ferrite. *b.* Large crystals of ferrite surrounded by carburized iron. *d.* Two zones of low-carbon (mild) steel and a zone of uncarburized (pure) iron.
2. Two pieces of iron from tripods, late eighth century B.C., Nimrud, Assyria (1953.6.1). Examination of a section shows a piled structure indicating that the tripod iron was made from piled wrought material.

PLATE II

- Socketed spear-head from Deve Hüyük, Syria, 600–500 B.C. (1953.1.32):
1. Radiograph taken before sectioning, showing light areas still metallic, and dark patchy areas (metal converted to oxide).
 2. Photomacrograph of polished and etched section showing layered structure.

PLATE III

- Deve Hüyük spear-head, continued:
1. Photomacrograph at mid length showing contorted piled structure. $\times 4$.
 2. Photomicrograph at mid length showing contorted piled structure and variable grain size. The layering is associated with high-carbon bands. $\times 25$.

PLATE IV

- Deve Hüyük spear-head, continued:
1. Photomicrograph from same field as Plate III, Fig. 2 taken at a higher magnification, showing mixed grain size, banding, and high-carbon layers. $\times 200$.
 2. Photomacrograph of transverse cross-section of socket at fractured position showing layered structure and copper filaments adjacent to butt brazed joint. *c.* $\times 4$.
 3. Photomicrograph of spear-head showing fine pearlitic carbide structure. $\times 1000$.

PLATE V

1. Photomicrograph of iron pick from Lachish (area destroyed *c.* 588 B.C.), close to point, showing entrapped slag at welding line and coarse Widmanstätten areas typical of material quenched from a very high temperature. $\times 100$. (Specimen lent by Miss Olga Tufnell.)
2. Photomicrograph of axe-edge, Hallstatt period, sixth century B.C., from Magdalenenberg, Yugoslavia: rather high-carbon wrought iron with numerous entrapped slag filaments. No sign of hardening. $\times 200$. (This specimen and the following sent by Naturhistorisches Museum, Vienna.)
3. Photomicrograph, lance-head, Hallstatt, sixth century B.C., showing blade of pure wrought iron with numerous entrapped slag filaments. No sign of hardening. $\times 200$.

EXPLANATION OF THE PLATES

PLATE VI

Spear-head from Vače, Jugoslavia, fifth century B.C. (1953.1.33): 1. Photomacrograph of polished and etched section showing high-carbon (dark area) portion welded to low-carbon material. Severe burning of the high-carbon area has occurred during heating for welding and forging. $\times 1.6$.

2. Enlarged photomacrograph of Fig. 1 showing central weld line, variable grain size, and local burning in (dark) high-carbon areas. $\times 4$.

3. Photomicrograph towards centre of spear-head showing junction zone between low-carbon area and (dark) high-carbon area. Vickers hardness 103 to 134. $\times 60$.

PLATE VII

Vače spear-head, continued: 1. Photomicrograph towards centre of spear-head showing fine ferrite grain size and (dark carbide) pearlitic areas. $\times 185$.

2. Photomicrograph near to point showing low-carbon wrought iron, with a very coarse grain size and slag patches not expelled during forging. $\times 185$.

3. High-power view of central portion of spear-point in relatively high-carbon area showing ferritic grain size with dark pearlitic carbide areas, indicating that spear-head was slowly cooled after forging. $\times 1,000$.

PLATE VIII

La Tène sword, *c.* 50 B.C., Switzerland (Historisches Museum, Basel, 1947.639): 1. Coarse ferritic grain size adjacent to central rib of blade. $\times 200$.

2. Blade at central rib showing large ferrite grains with numerous Neumann bands. $\times 200$.

3. Structure close to edge of blade where grain size is fine and ferrite grains show pronounced veining. $\times 200$.

PLATE IX

La Tène sword, *c.* 50 B.C., Switzerland (Historisches Museum, Basel, 1947.640):

1. Photomacrograph showing piled structure and corrosion pits. $\times 7$.

2. Photomicrograph from central rib. $\times 200$.

PLATE X

La Tène sword (1947.640) continued: Photomicrograph from cutting-edge. $\times 200$.

PLATE XI

Tanged knife from Oxyrhynchus, Egypt, Roman period (Pitt Rivers Museum): 1. Photomacrograph (slightly enlarged) of polished and etched longitudinal section, showing contorted layered structure, indicating blade has been built up by welding and forging a number of wrought-iron faggots.

2. Photomacrograph of portion of blade showing layered structure and entrapped slag filaments. $\times 12$.

3. Photomicrograph of body of blade showing ferrite grains containing numerous Neumann bands, indicating that the blade was hammered cold after forging. The structure shows numerous particles of entrapped slag. $\times 200$.

EXPLANATION OF THE PLATES

PLATE XII

1. Roman saw, Oxyrhynchus, Egypt (Pitt Rivers Museum): Photomicrograph close to teeth showing structure typical of a low-carbon steel which has been hot worked on a falling temperature. $\times 200$.
2. Roman ring and tweezers, Harageh, Egypt (Newbury, Borough Museum): Photomicrograph at end of blades. This structure is typical of a carburized wrought iron which has been hot worked on a falling temperature, followed by annealing at a low temperature where carbides have become agglomerated. $\times 200$.
3. Roman ring and staple, Harageh (Newbury, Borough Museum): Photomicrograph of staple end showing piled structure with numerous entrapped slag filaments. The background structure is typical of a 0.25 per cent. carbon steel which has been hot worked on a falling temperature, resulting in a very mixed grain size. $\times 200$.
4. Area similar to Fig. 3, enlarged. $\times 1,000$.

PLATE XIII

1. Frilford, Berkshire, Roman knife, third to fourth century A.D. (1953.1.34): Print from X-ray negative. Close examination of this negative shows a fibrous structure typical of wrought iron. The only solid metallic portion is at the junction of the tanged end of the beginning of the blade.
2. The same: Transverse cross-section from end of tanged knife, showing piled wrought structure. Only small portions of the wrought material remain. The bulk of the blade has been converted to iron hydroxide. $c. \times 8$.
3. The same: Photomicrograph of uncorroded portion showing coarse ferritic grain size typical of low-carbon wrought iron. $\times 400$.
4. Roman axe, fourth century A.D., Silchester, Hampshire (Reading Museum and Art Gallery): Photomicrograph up to the edge showing piling and highly contorted flow lines roughly parallel to the edge (top). Lower right-hand side shows a heavy layer of hard rust and corrosion pits. $c. \times 10$.

PLATE XIV

- Roman axe, Silchester, continued: 1. Photomicrograph of light areas in Plate XIII, Fig. 4, showing elongated slag filaments in low-carbon bands at welding lines. $\times 200$.
2. Photomicrograph of dark high-carbon areas shown in Plate XIII, Fig. 4. $\times 200$.
 3. Photomicrograph of similar areas to Fig. 2 showing ferritic background with partially spheroidized network carbides. $\times 1,000$.
 4. Saxon axe-edge (Reading Museum and Art Gallery). Photomicrograph close to edge showing large ferritic grain size and numerous Neumann bands indicating the edge was hammered cold. $\times 120$.

PLATE XV

- Danish battle-axe, A.D. 895 or 896, bed of River Lea near Stratford, Essex (1954.11.11):
1. Photomicrograph up to cutting-edge showing carburized zone on the immediate edge, and flow pattern due to forging. Background structure is of wrought low-carbon iron. $\times 4.5$.

EXPLANATION OF THE PLATES

2. Photomicrograph of cutting-edge showing coarse martensitic structure. Vickers hardness 450. Dark areas non-metallic entrapped cinder not expelled during the piling and forging operation. $\times 250$.
3. Higher-power view of Fig. 2 showing coarse martensitic structure of cutting-edge. Vickers hardness 450. $\times 1,000$.
4. Background of blade, showing structure of wrought low-carbon iron and entrapped cinder. Vickers hardness 160 to 170. $\times 200$.

PLATE XVI

1. Mediaeval barbed and socketed arrow-head, Woodeaton, Oxon. (1953.1.35): Print from X-ray negative. Light areas show corrosion pits and slag streaks.
2. Longitudinal cross-section polished and etched, showing heavily corroded areas and fibrous slag streaks. Socket portion has been formed from thin wrought-iron sheet wrapped round a pointed former. Wings and point of the arrow-head have been imperfectly forge welded on to the socket. $\times 2$.
3. Enlarged view of socket, showing marked banding, cinder filaments, and mixed grain size. $\times 18$.
4. Photomicrograph of portion of wings of the arrow-head, showing typical wrought-iron structure with ferritic grains and cinder filaments. The arrow-head is in the as-forged condition and no attempt has been made to harden it. Vickers hardness 115 to 153. $\times 200$.

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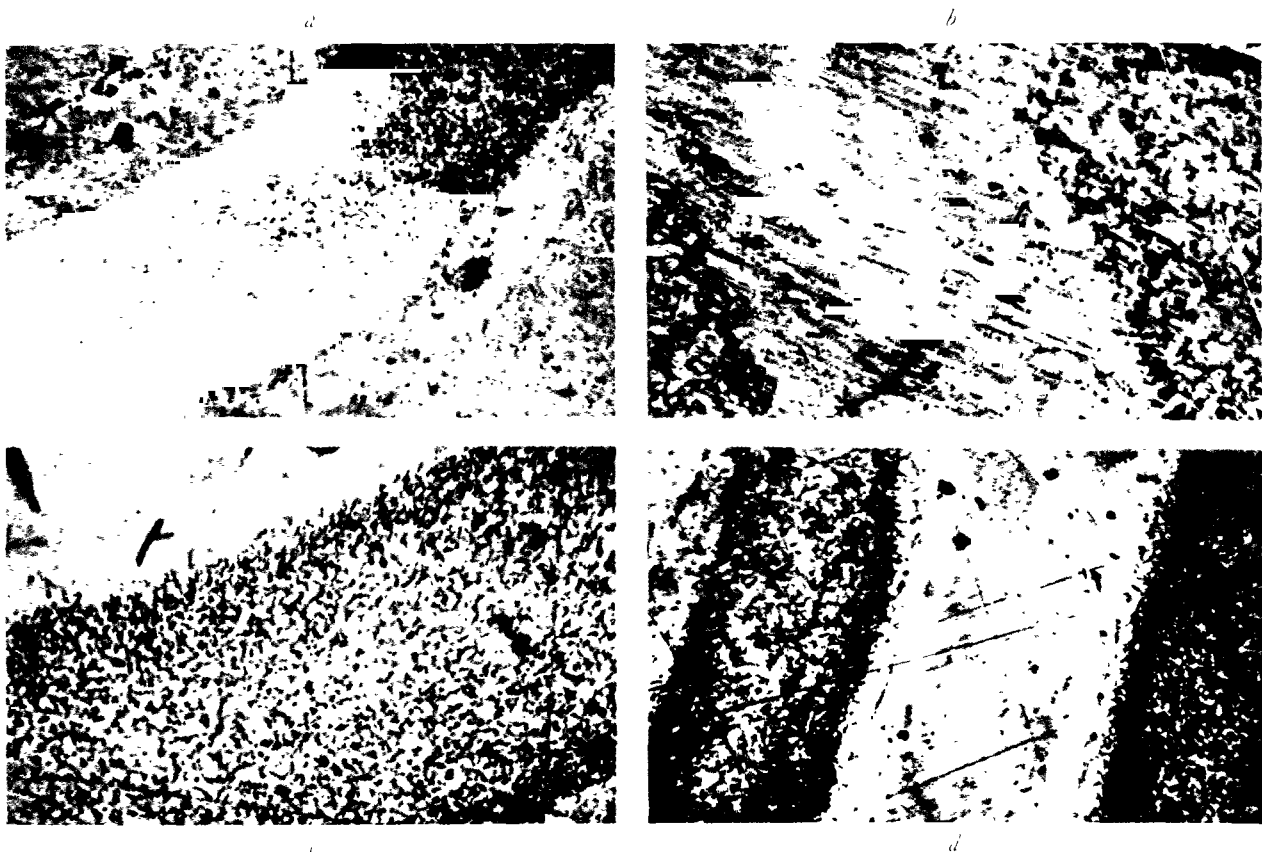
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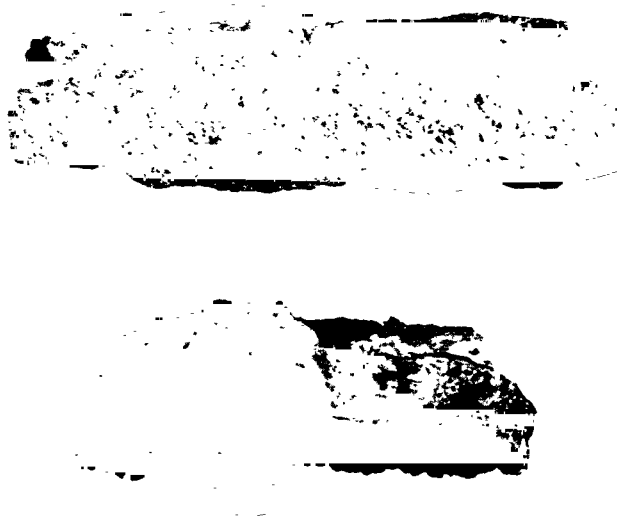
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1. Photomicrographs of the surface of a sword (France-Lanord 1949)



2. Pieces of iron tripods, Nimrud, 8th century B.C.



FIG. 1. Radiograph of Dove Huvuk Spear-head taken before sectioning, showing light areas still metallic, and dark patchy areas (metal converted to oxide)



FIG. 2. Photomicrograph of polished and etched section of above showing layered structure

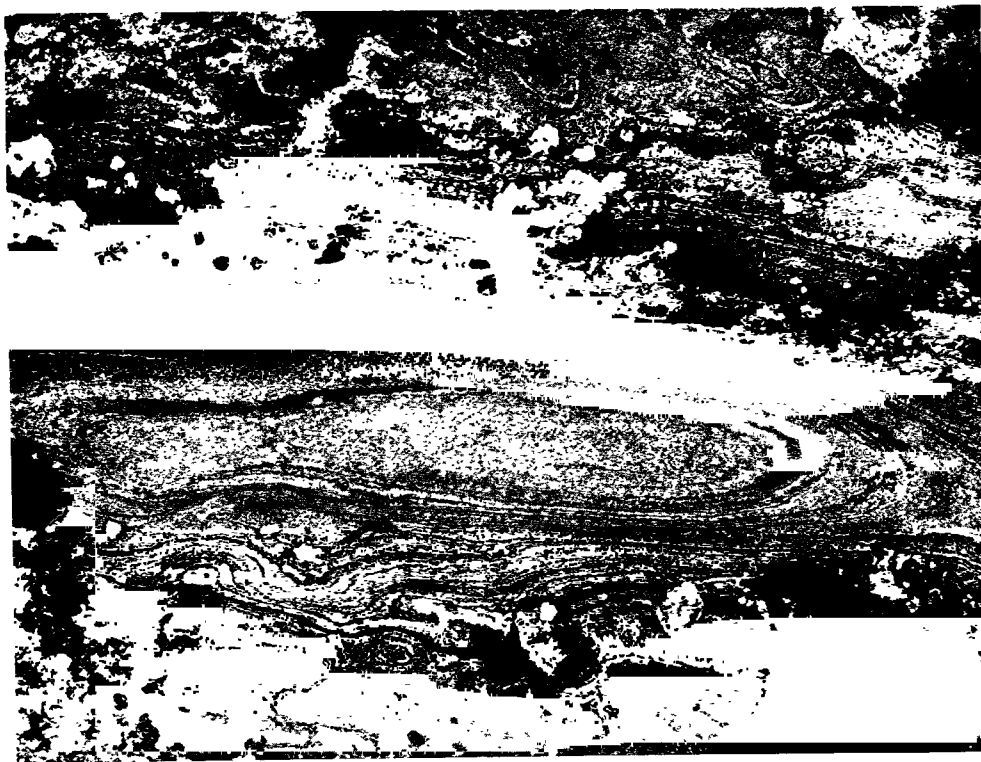


FIG. 1. Photomicrograph of Deve Huvuk Spear-head showing contorted piled structure 4



FIG. 2. Photomicrograph of the same. 25

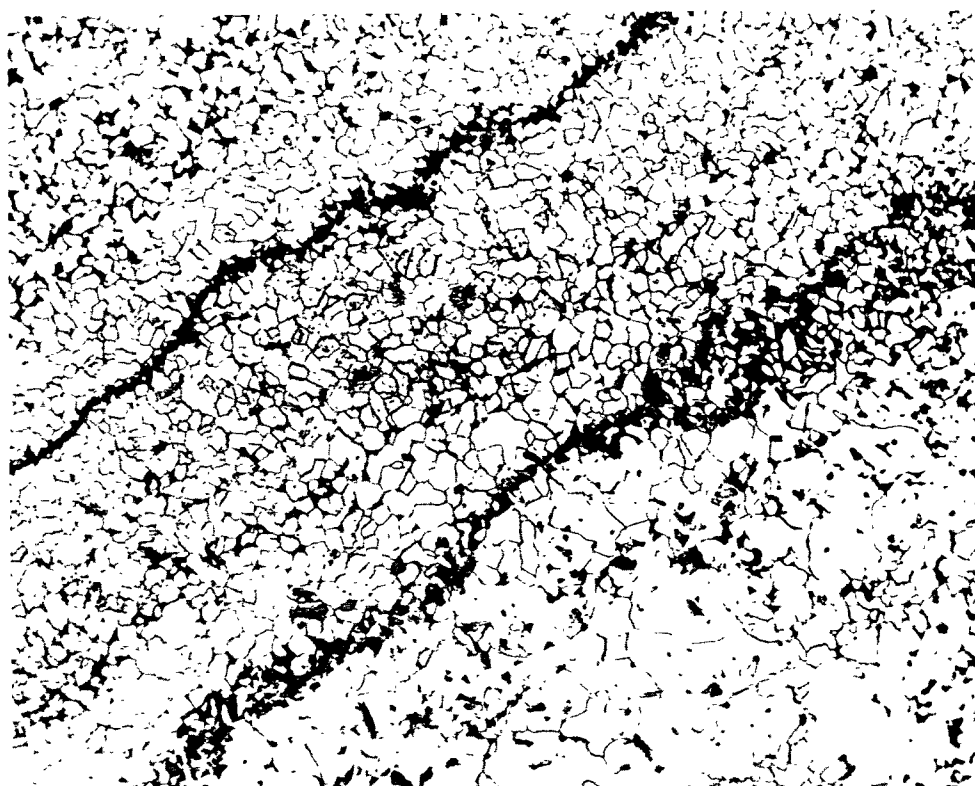


FIG. 1. Photomicrograph from same field as Plate III, Fig. 2. 200



FIG. 2. Photomicrograph of cross-section of socket. 4

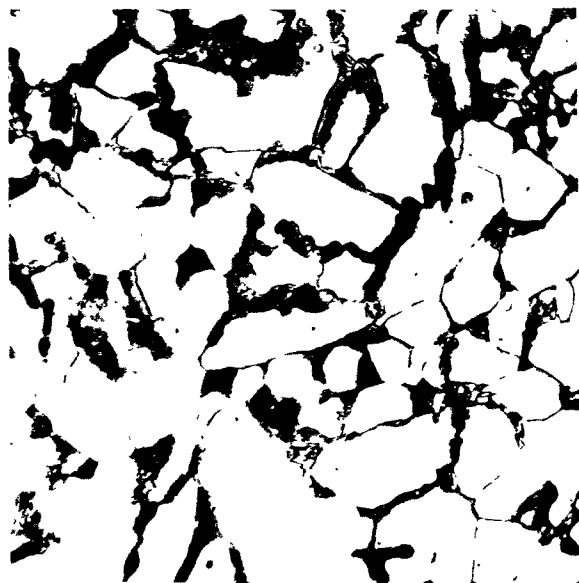


FIG. 3. Photomicrograph showing fine pearlitic carbide structure. 1000

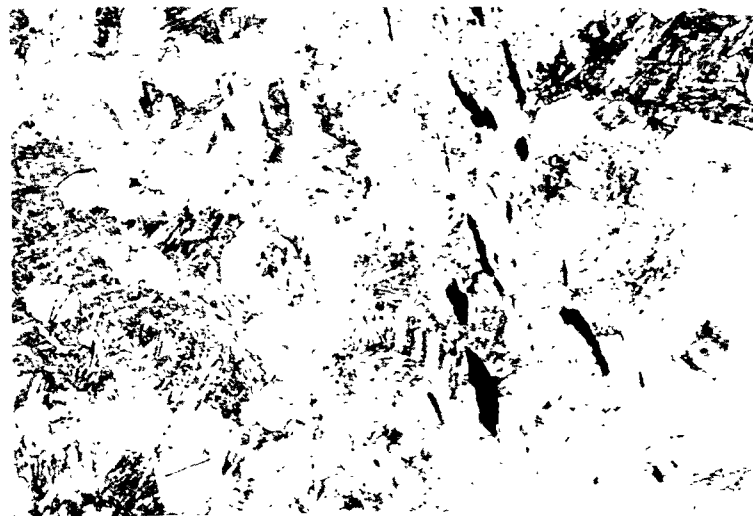


FIG. 1. Photomicrograph near point of Lachish pick showing Widmanstätten areas. $\times 1000$



FIG. 2. Photomicrograph, axe-edge, Magdalenenberg. $\times 200$
N.Y. 6.292

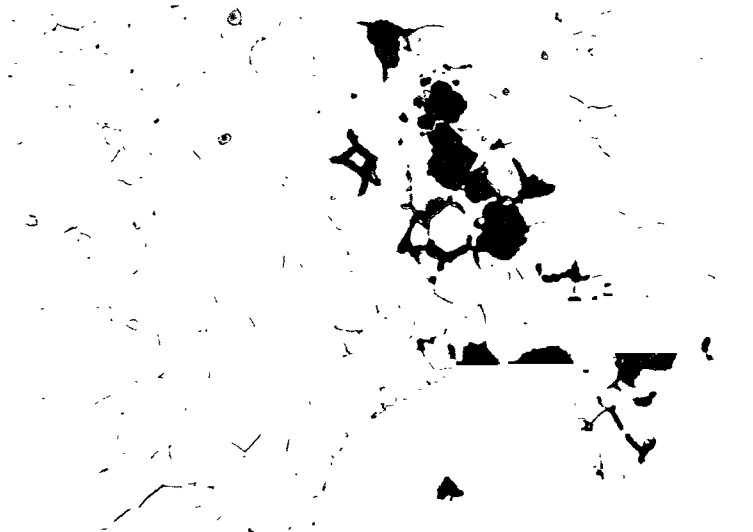


FIG. 3. Photomicrograph, lance-head, Hallstatt. $\times 200$

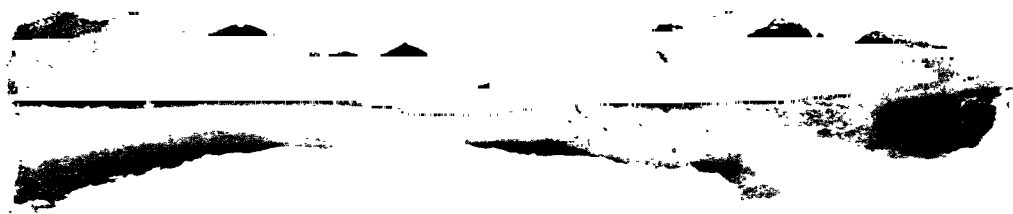


FIG. 1.
Photomicrograph.
1·6

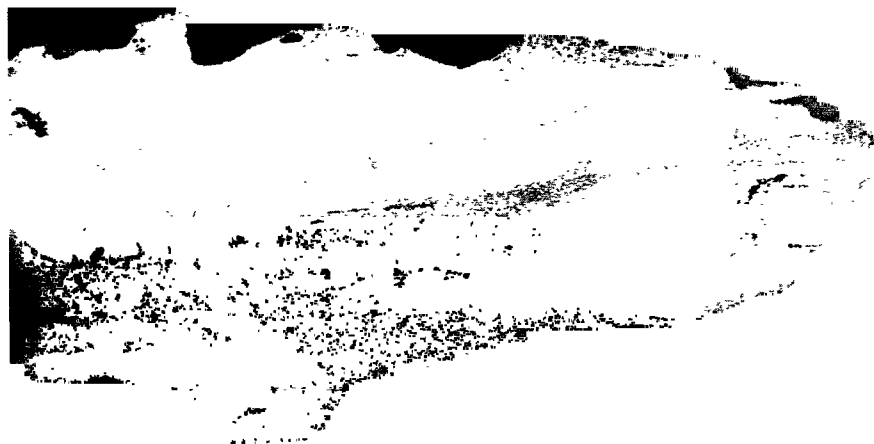


FIG. 2.
Photomicrograph
+



FIG. 3. Photomicrograph near
centre, 6c

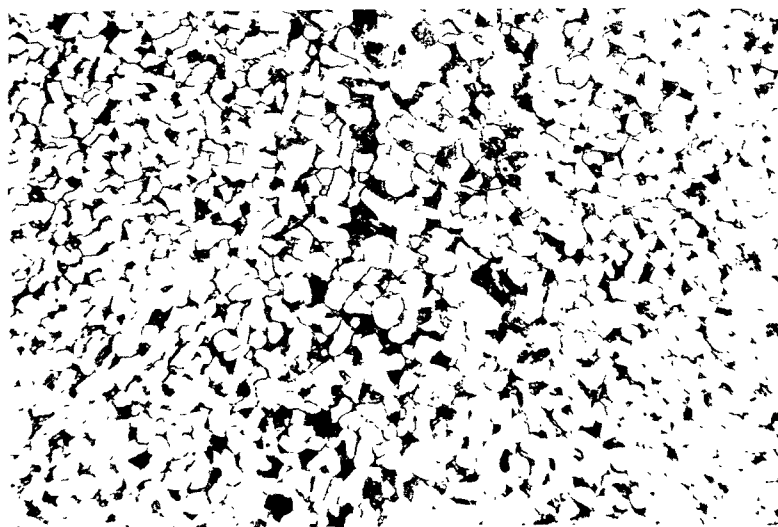


FIG. 1 Photomicrograph towards centre
185



FIG. 2 Photomicrograph near point.
185



FIG. 3 Photomicrograph of central portion of
point. 1000

VACE SPEAR-HFAD
No. 7, 200

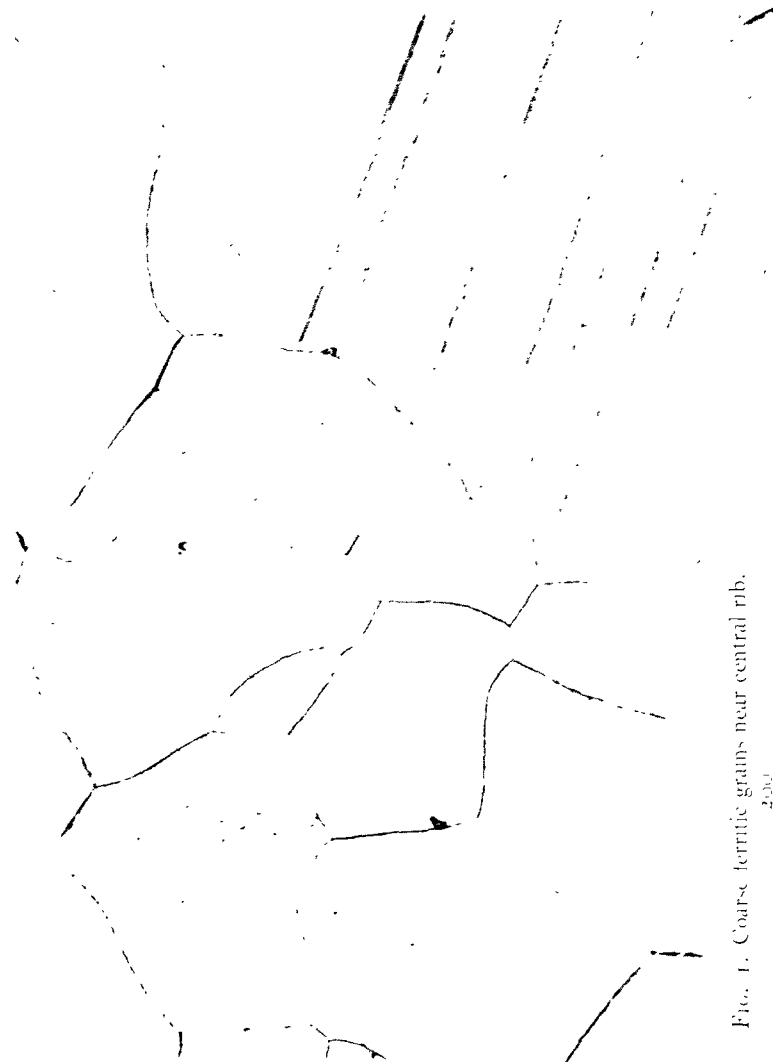


FIG. 1. Coarse ferritic grains near central rib.
200

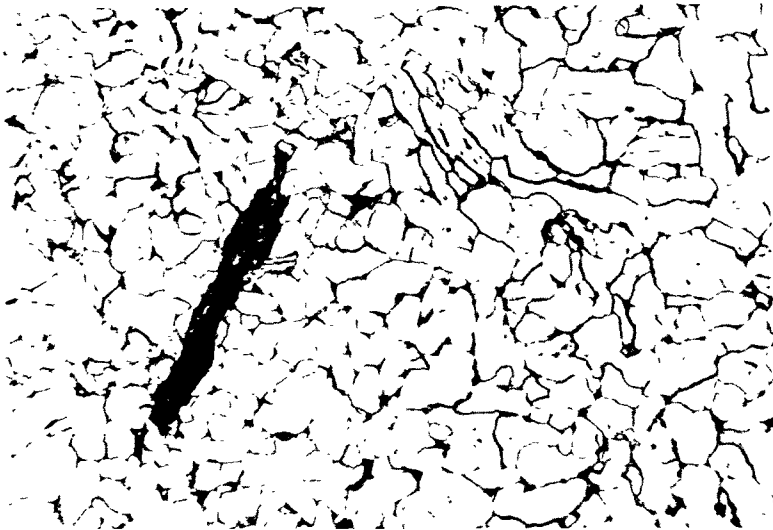


FIG. 3. Structure near edge of blade where grain size is fine and ferrite grains show pronounced veining.
200

FIG. 2. Photomicrograph at central rib showing large ferrite grains and Neumann bands.
200

LA TÈNE SWORD (1947.639)
See p. 203



FIG. 1 Photomicrograph showing pitted structure and corrosion pits.

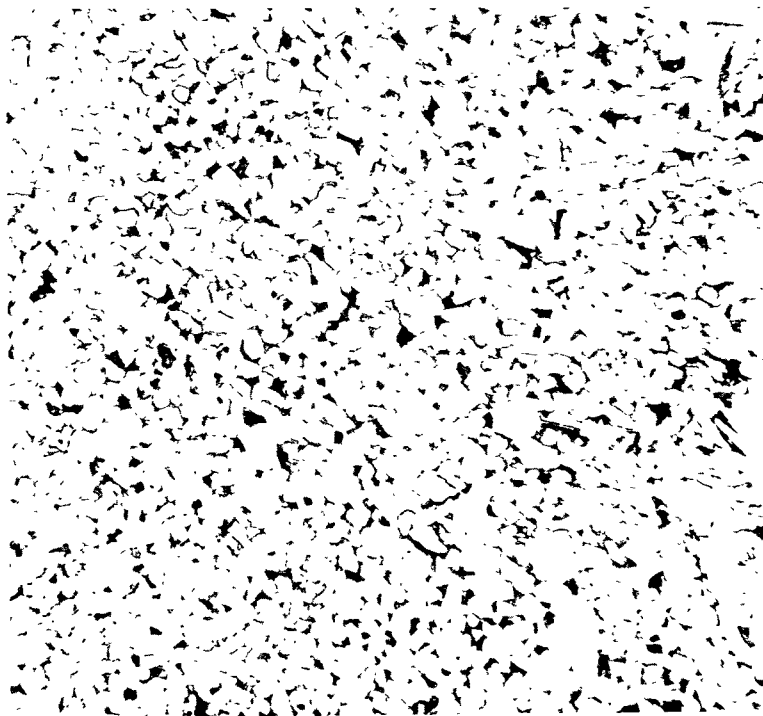
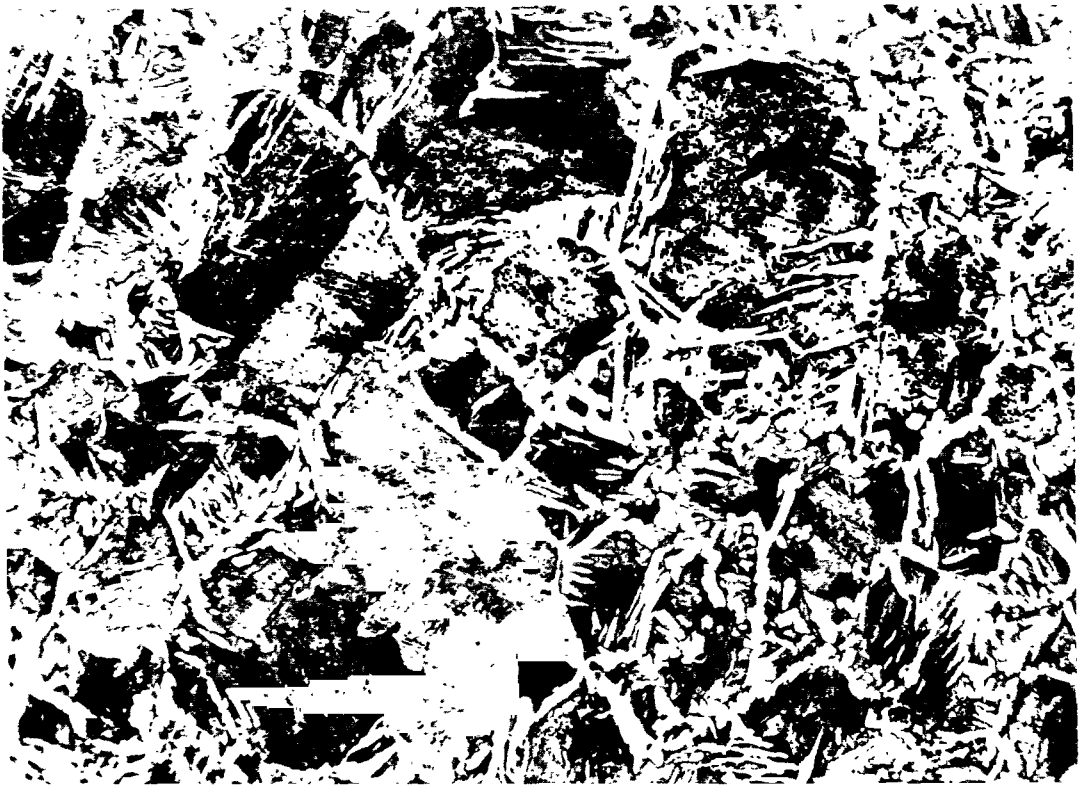


FIG. 2 Photomicrograph of central rib.

LE TINE SWORD (1947.640)

81.6.203



Photomicrograph from cutting-edge. 200

LA TÈNE SWORD (1947.640)

N. p. 293



FIG. 1. Photomicrograph of Oxyrhynchus knife, slightly enlarged

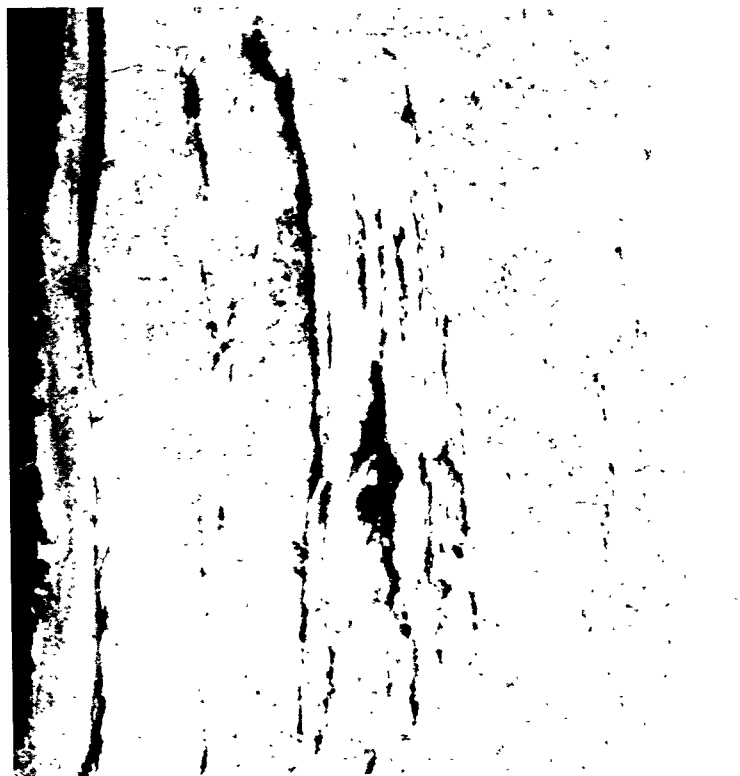


FIG. 2. Photomicrograph of part of blade showing layered structure.

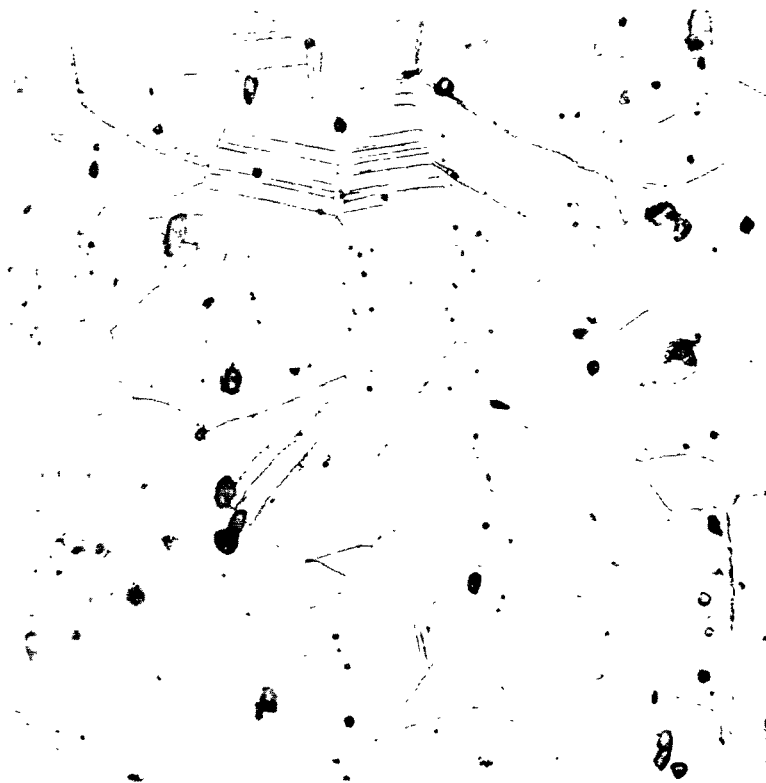


FIG. 3. Photomicrograph showing territe grains containing Neumann bands



FIG. 1. Roman saw, Oxyrhynchus. 200

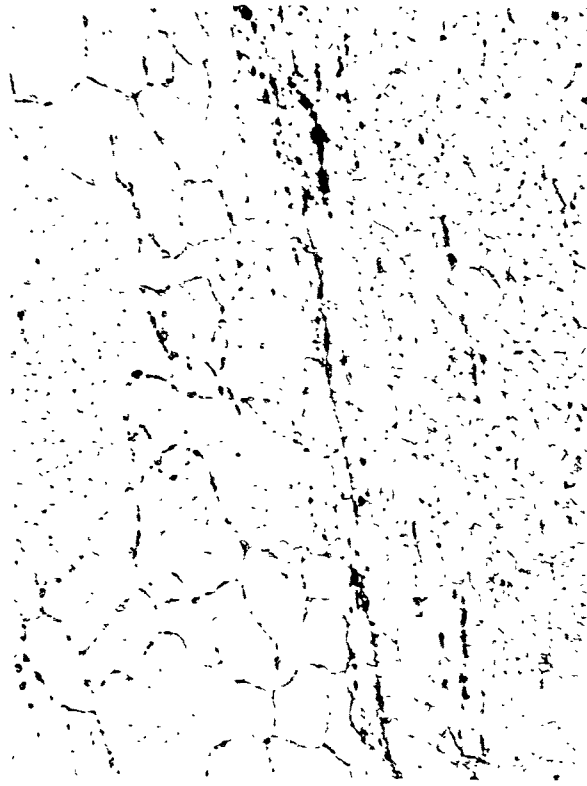


FIG. 2. Roman tweezers, Egypt. 200



FIG. 3. Roman staple-end, Egypt. 200

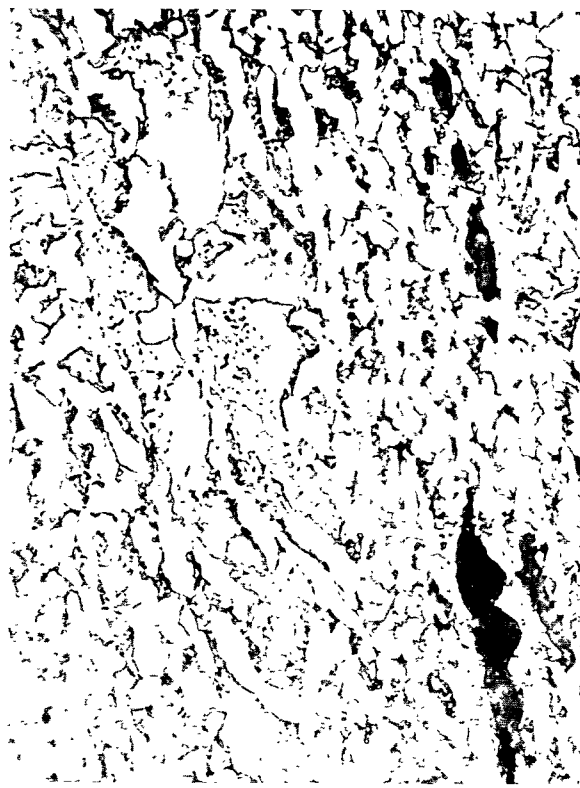


FIG. 4. As Fig. 3. 1000



FIG. 1. X-ray,
Roman knife, Fril-
ford

FIG. 2. Cross-section
from end of Frilford
knife, ca. 800

FIG. 3. Photomi-
crograph of Frilford
knife, 400

FIG. 4. Photoma-
crograph, Roman
axe-edge, Silchester,
ca. 100



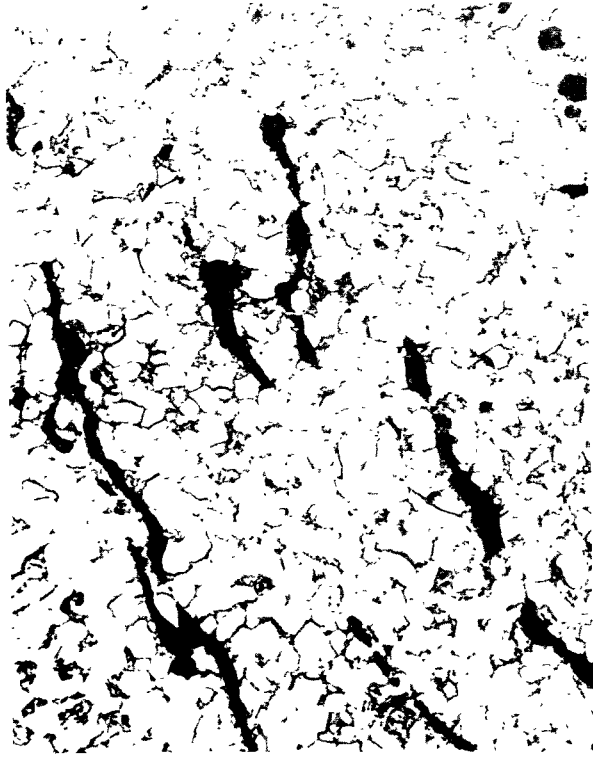


FIG. 1. Roman ave, Silchester. 200

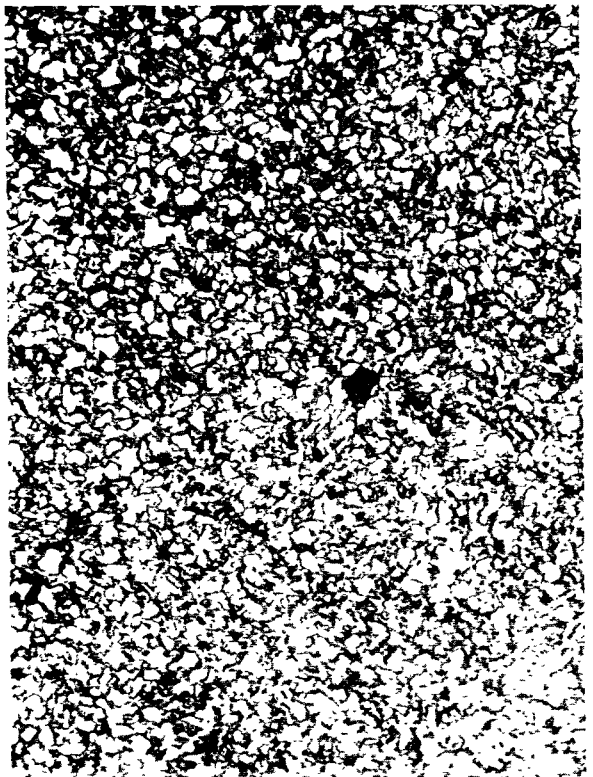


FIG. 2. Roman ave, Silchester. 200

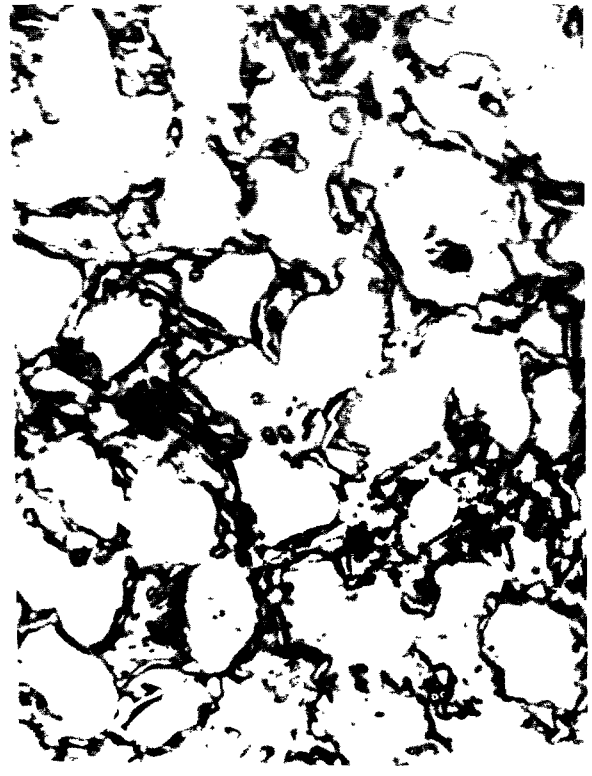


FIG. 3. Roman ave, Silchester. 1000

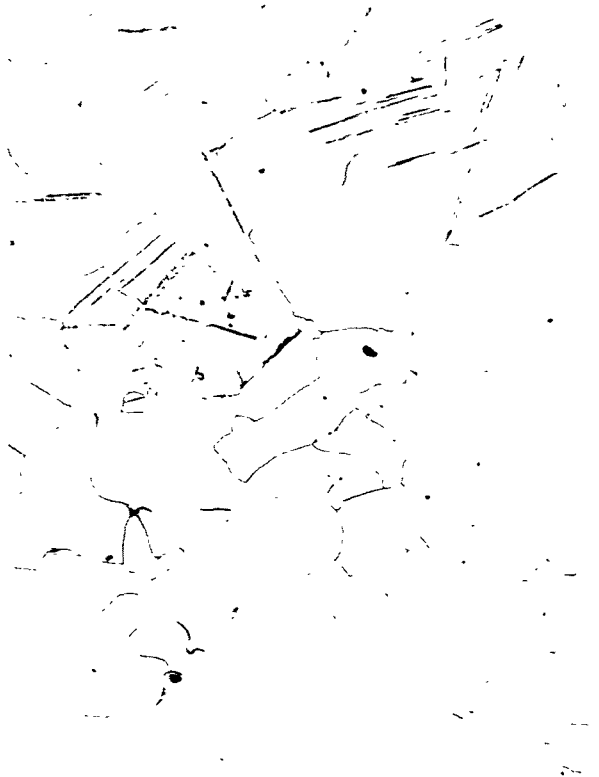


FIG. 4. Savon ave-edge. 120



FIG. 1 Photomicrograph of Danish battle-axe, cutting-edge. 45



FIG. 2 Photomicrograph of same, cutting-edge. 250



FIG. 3 As Fig. 2. 100

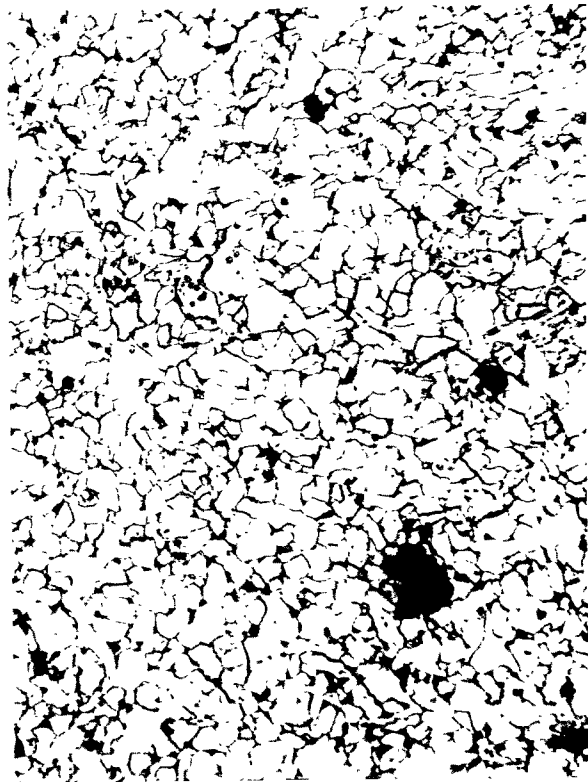


FIG. 4 Background of blade. 200



FIG. 2. Longitudinal cross-section.

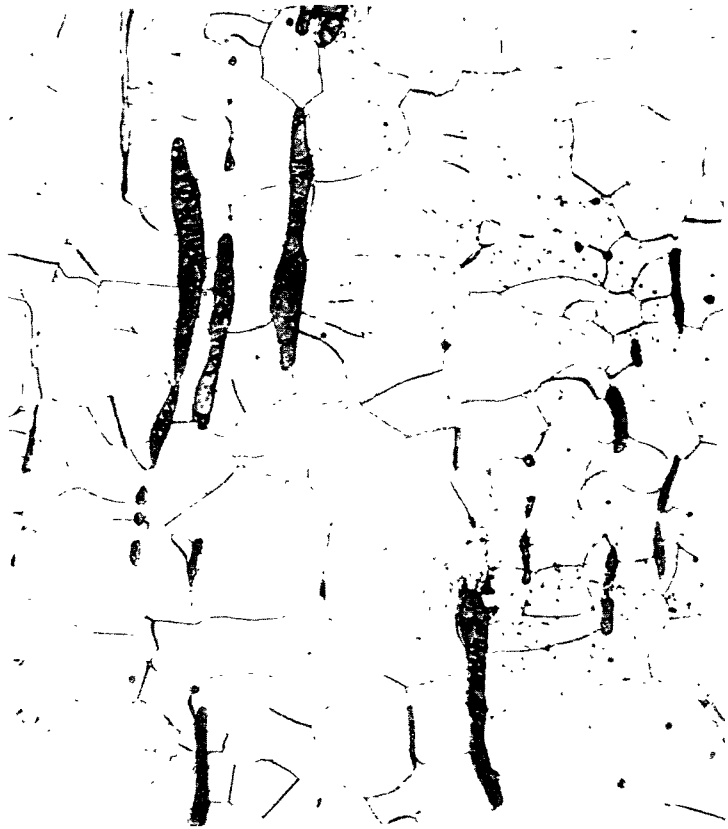


FIG. 1. Nerve



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kg. of nitric acid per hectare may fall annually in rainfall. An annual accession of assimilable nitrogen of this magnitude, if shown to be general, might sufficiently account for the nitrogen nutrition of plants and the soil nitrogen of the tropics. Under the conditions obtaining in temperate and cold climates, however, it is necessary to examine other sources of supply.

In the early years of the nineteenth century, the great authority of Liebig was lent to the theory that plants obtained their nitrogen from the traces of ammonia present in the atmosphere, and that the use of nitrogenous fertilizers was as superfluous as the use of fertilizers to supply carbon. The careful experiments of Lawes and Gilbert at Rothamsted, however, clearly demonstrated the dependence of plants on supplies of available nitrogen in the soil. Leguminous plants were an apparent exception, according to field experiments, which actually demonstrated a gain in soil nitrogen consequent on the growth of such crops. In practice, the favourable effect following the growth of leguminous crops had long been known, and is suggested by the familiar lines from Virgil's First Georgic.

In 1858, Lachmann²² showed that the nodules which had been observed in the roots of leguminous plants contained bacteria. The problem was cleared up by H. Hellriegel and H. Willfarth²³ in 1888, and the bacteria, finally isolated by M. W. Beijerinck²⁴, are now known by the name *Bact. radicola*. These bacteria live in symbiosis with their hosts and have the ability to bring atmospheric nitrogen into organic combinations. The nitrogen thus fixed from the air is available for the nutrition of the host plant, from which in turn the bacteria draw their non-nitrogenous pabulum. They are aerobic organisms and appear to exist in forms associated with particular species of leguminous plants.

Certain other plants, notably the alder (*Alnus*), also exhibit nodule formation and form symbiotic associations with bacteria of the *Bact. radicola* group. Symbiotic nitrogen fixation in the genus *Casuarina* has been studied by H.

Mowry²⁵. V. P. Noglev²⁶ reports an organism, *Bacillus alopecuri* (n.sp.) living in symbiosis with the roots of *Alopecurus pratensis* (meadow foxtail) capable of fixing nitrogen. Nitrogen fixation may possibly take place also through mycorrhiza. R. Brown²⁷ postulates such a fixation by the endophyte of *Lolium*.

In addition to the nitrogen fixation effected by *Bact. radicola* in symbiosis with leguminous plants, there is another group of bacteria able to build up atmospheric nitrogen into organic combination without the co-operation of a host plant. The free-living nitrogen fixers are heterotrophic organisms depending for their existence on a supply of soluble carbohydrates. The first species, discovered by S. Winogradsky²⁸ in 1893, namely, *Clostridium pastorianum*, is an anaerobic organism, originally isolated from pond mud. Under laboratory conditions, it can fix 2-3 mg. of nitrogen per gram of carbohydrate utilized. There is little doubt that bacteria of the *Clostridium* type play an important part in the nitrogen economy of soils with deficient aeration and even of normal soils during periods of deficient aeration.

In 1894, M. W. Beijerinck²⁹ discovered an aerobic heterotrophic organism, *Azotobacter chroococcum*, which, like *Clostridium*, utilizes soluble carbohydrates and fixes elementary nitrogen. It appears to be more efficient than *Clostridium* and fixes about 10 mg. of nitrogen per gram of carbohydrate oxidized. *Azotobacter* is more sensitive to acid reaction than *Clostridium* and is generally considered to be inactive in media more acid than pH 6.0. J. K. Wilson and B. D. Wilson³⁰, however, working with New York peat soils, found no relationship between soil reaction and the presence of *Azotobacter*. They consider the nature of the soil complex of more importance than the pH.

Other bacteria are known which can fix atmospheric nitrogen, and symbiotic associations between such organisms and algæ have been demonstrated. The direct fixation of nitrogen by higher plants, though occasionally reported, still lacks conclusive proof. F. E. Allison and S. R. Hoover³¹

report fixation of nitrogen by the blue-green alga, *Nostoc*. P. K. De³² reports the fixation of nitrogen by algae in Indian rice fields.

During recent years, Indian soil micro-biologists have put forward the possibility that nitrogen fixation may occur by photochemical action. The presence of oxidizable carbohydrate appears to be necessary. Thus N. R. Dhar and E. V. Seshacharyulu³³ found that nitrogen fixation in sugar treated soils was greater in sunlight than in darkness. N. R. Dhar and S. K. Mukherji³⁴ found that admixture of plant leaves, sawdust, straw, etc., increased nitrogen fixation in sunlight.

SULPHUR CYCLE IN SOILS

Sulphur is present in soils mainly in the form of cystine groups associated with the proteins of organic matter. In addition, under anaerobic conditions, sulphides and even free sulphur may be present.

Certain bacteria in the soil have the ability to oxidize organic sulphur compounds, sulphides, and free sulphur to sulphuric acid or sulphates. These are aerobic bacteria whose activity appears to be favoured by the presence of calcium carbonate. Broadly speaking, it may be said that the same conditions which favour nitrification also favour the production of sulphates.

Sulphuric acid from the biological oxidation of organic sulphur compounds may contribute appreciably to the acidity of peat soils. P. Köttgen and Rörig³⁵ found that from 7.7 to 53% of the total acidity of forest peat soils was due to sulphuric acid. High base-status favours sulphofication and may thus accelerate lowering of the pH. Dressings of sulphur are sometimes applied to the soil to increase acidity.

Under anaerobic conditions, sulphates are readily changed into sulphides, including hydrogen sulphide, whose odour is frequently evident in subaqueous horizons.

CARBON-NITROGEN RATIO OF SOIL ORGANIC MATTER

A consideration of the composition of the plant materials added to the soil from the residues of vegetation will show that their ratio of carbon to nitrogen is in the region of 40:1. The organic matter of soils shows a much narrower carbon-nitrogen ratio. For the soils of temperate regions, the ratio approaches 10:1. Only a small proportion of the organic matter in soils consists of unaltered plant residues, and the carbon-nitrogen ratio observed represents the character of the actual soil humus. Sufficient data are not yet available for a satisfactory judgement to be formed as to the effect of climate on the C:N ratio. From a study of soils of the United States, H. Jenny¹⁶ concludes that the ratio widens with decreasing temperature, but W. McLean³⁷ has examined many tropical soils which give C:N ratios considerably greater than 10:1.

M. S. Anderson and H. G. Byers³⁸ have examined the application of the C:N ratio to soil classification. Wide variations occur within the groups, the most constant figure, 9.0, being given by the chernozems. The widest ratios, 21.4-22.6, occur in the podzols. It is unlikely that the C:N ratio can give more than a crude indication of the nature of soil organic matter. A wide ratio may be caused by the presence of much undecomposed plant materials or of elementary carbon, the latter forming no inconsiderable contribution in cultivated soils and in soils subject to forest or bush fires.

The addition to soil of organic matter with a wider carbon-nitrogen ratio than that characteristic for the soil is followed by a considerable evolution of carbon dioxide. The organisms concerned in this change require a supply of available nitrogenous compounds and there is thus a temporary diminution in the content of ammoniacal and nitric nitrogen. In the absence of fresh organic matter it may be supposed that losses of carbon and nitrogen from the soil by micro-biological decompositions will be approximately in the proportion in which they occur in the characteristic organic matter of the soil.

THE CONSTITUTION OF SOIL ORGANIC MATTER

The nature and constitution of soil organic matter has long presented a difficult problem for soil chemists. Its complexity was recognised at an early stage by the first workers in the subject. One of the chief difficulties in investigating the problem is the impossibility of isolating the organic matter of ordinary soils from its accompanying mineral matter. It was inevitable, therefore, that much of the earlier work was carried out on peats, consisting wholly or mainly of organic matter. And since the mode of origin of such organic matter is different from that in the majority of ordinary soils, it is probable that the results obtained are only of limited application.

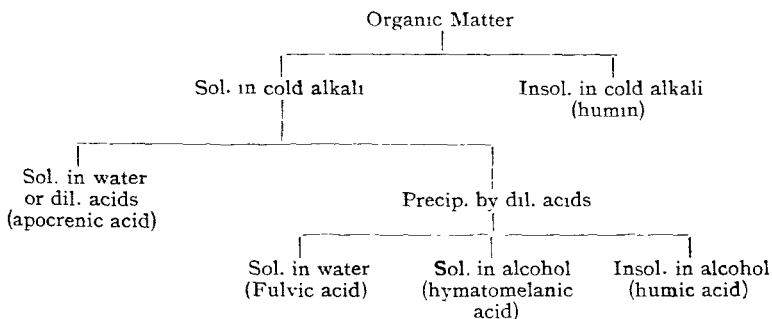
G. W. Robinson and J. O. Jones³⁹ suggested a simple fractionation of soil organic matter into humified and non-humified by the use of boiling 6% hydrogen peroxide as a reagent. The assumption underlying this method of determining the degree of humification was, however, questioned by W. O. Robinson⁴⁰, who showed that, in the presence of soil, cellulose is appreciably attacked by 6% hydrogen peroxide. The peroxide method for determining the degree of humification of soil organic matter has, however, found a certain application in the study of forest soils. For example, A. Něméc⁴¹ was able to distinguish different types of forest humus by the use of this reagent.

The fundamental problem of soil organic matter is the nature and mode of origin of the characteristic organic soil constituent, humus. As far back as 1786, F. K. Achard* extracted a black substance from peat by the action of alkali, and this gave the impetus to numerous attempts to isolate complex acids and other related compounds from peats and also from mineral soils. In this way, such compounds as humic acid, ulmic acid, crenic acid, apocrenic acid, humin, and ulmin were distinguished. But, inasmuch as they are non-crystalline substances of exceedingly complex composi-

* Cited in "Humus," p. 22, by S. Waksman, London, 1936.

tion, their identity as definite chemical compounds has always been open to doubt.

A possible fractionation of soil organic matter is shown in the following scheme:—



The very existence of humic and similar acids was called into question by certain workers, notably E. Gully⁴², who considered that the phenomena of extraction by alkalies and precipitation by acids were explainable as colloidal absorption effects.

The existence of acids in peat was placed beyond doubt by the work of S. Odén⁴³, who showed that the conductometric curves obtained by adding increasing amounts of alkali to peat or prepared humic acids were such as could only be given by weak insoluble acids.

Odén concluded that humic acid has the formula $C_{60}H_{52}O_{24}(COOH)_4$. Its aqueous suspension has a pH of 4.5. It should be remarked, however, that pH values of less than 4 are frequently encountered in podsol profiles under heath peat.

O. Schreiner and E. C. Shorey⁴⁴ succeeded in isolating a number of definite compounds from soil organic matter. Included in the humic acid fraction, they found paraffinic acid, agrocenic acid, $C_{26}H_{44}O_3$, agosterol $C_{26}H_{44}O$, and phytosterol, $C_{26}H_{41}O.H_2O$. In the fraction not precipitated by acids (crenic and apocrenic group) they found dihydroxystearic acid, α -picoline- γ -carboxylic acid, xanthine,

hypoxanthine, cytosine, histidine, and arginine. No complete fractionation was effected and it is possible that some of the compounds isolated were not originally present as such in the soil, but were formed by the processes of extraction used by these workers.

It has long been known that, by the action of strong hydrochloric acid on sugar, various substances similar in appearance to humus can be obtained, and it was supposed that they might be similar in origin and constitution. Artificially prepared humic acid is, of course, free from nitrogen, whereas natural humic acid always contains nitrogen; but it was thought possible that such nitrogen might be present in adventitious compounds which were not essential constituents of humus. It was, however, found possible to prepare artificial humic acids containing nitrogen by condensation of sugars with amino-acids. L. C. Maillard⁴⁵ actually suggested this mode of origin in the soil.

V. H. Beckley⁴⁶ demonstrated the formation of humus from carbohydrates by way of furfuraldehyde or methyl-hydroxyfurfuraldehyde, which undergo condensation to form humus. W. Eller⁴⁷ suggested an entirely different mode of origin by way of benzene derivatives. Humic acids prepared artificially by the oxidation of phenol derivatives were shown to resemble closely the humus of soil.

The fact that humus has a dark colour has tended to obscure the possibility that a considerable proportion of it may consist of materials which have survived from plant residues. R. A. Gortner⁴⁸ found that alkaline extracts similar to those obtained from soils could also be obtained from unchanged vegetable materials. He suggested that the only characteristic soil constituent is a black pigment, probably of bacterial origin, which rarely exceeds 40% of the humus obtained by alkaline extraction. The pigment, which is poor in nitrogen, is soluble in aqueous ammonia.

During recent years interest has centred round the origin of humus from the lignin and protein of plant residues. Starting from the suggestion of F. Fischer and H. Schrader⁴⁹

that lignin was the mother-substance of humus, S. A. Waksman and his co-workers have conclusively demonstrated the important rôle of this substance in the transformations of soil organic matter. Thus, in 1926, Waksman⁵⁰ suggested that the alkali-soluble humus of soils consists of two main categories, namely, (a) lignin, which being unattacked by micro-organisms, persists from added plant materials; and (b) microbial protoplasm and its decomposition products. The substances in the second group contain nitrogen. M. S. Du Toit and H. J. Page⁵¹ found a correlation between loss of lignin and gain in humus.

S. A. Waksman and K. R. Stevens⁵² proposed the application to soil organic matter of a system of proximate analysis used for plant materials. The results for the organic matter of some typical soils are shown in Table XIII. The ether-soluble fraction includes essential and fatty oils, wax- and resin-like substances, nitrogenous fats, etc. The alcohol-soluble fraction includes waxes, resins, alkaloids, tannins, and chlorophyll. Hemicellulose includes pentosans and hexosans. Cellulose includes celluloses and chitin-like substances. Lignin-humus is given by difference.

TABLE XIII.—COMPOSITION OF ORGANIC MATTER FOR SOME TYPICAL SOILS. CALCULATED ON BASIS OF SOIL ORGANIC MATTER = $C \times 1.72$ (WAKSMAN AND STEVENS)

SOIL	Ether Soluble	Alcohol Soluble	Hemi-Cellulose	Cellulose	Lignin Humus Complex	Protein
Summit soil, 4.49% org. matter ...	3.56	0.58	5.44	3.55	43.37	33.78
Kansas chernozem, 5.98% org. matter	4.71	1.53	8.60	5.22	40.81	34.74
Alberta chernozem, 11.20% org. matter	0.80	0.82	5.53	4.12	41.87	37.35
Carrington loam, 6.48% org. matter	0.62	0.62	8.21	3.64	42.29	30.38

Compared with plant residues such as straw and leaves, the soil organic matter contains much less of the hemi-cellulose and cellulose fractions. On the other hand, there is a considerable increase in the lignin fractions and the protein fraction. It appears unlikely that the lignin shown in the above system of fractionation is identical with plant lignin, whilst the identity of organic matter protein with plant protein is, as will be seen later, also improbable. Whatever be the nature of these fractions, they appear to account for 75% of the total organic matter of the soil.

The peats present a special type of distribution among the different fractions. Whilst in fen peats, cellulose is almost absent, in high moor (sphagnum) peats, considerable proportions of cellulose and hemi-celluloses appear to survive decomposition. Protein is considerably higher in low moor than in high moor peat.

N. P. Remesnov⁵³ has examined different kinds of soil by Waksman's methods and finds important differences. Thus, celluloses and hemi-celluloses are absent from grey soils and protein predominates over lignin humus. In chestnut earths hemi-celluloses appear, whilst lignin humus is greater than protein. In chernozems the lignin humus is 2.5-3 times the protein.

It soon became evident that both the lignin and the protein of humus differ from the original lignin and protein of plant residues. For example, W. T. McGeorge⁵⁴ showed that humus lignin possesses a higher base exchange capacity than plant lignin. According to H. Pallmann⁵⁵, humic acid shows a higher exchange capacity, probably due to increase in the proportion of carboxyl groups, which are absent from lignin, and a higher degree of oxidation as shown by the O:C ratio. It may be intermediate in properties between lignin and graphitic acid. Further, the protein of humus differs markedly from the protein of plant materials in being resistant to nitrification. R. P. Hobson⁵⁵ considered the "humic acid complexes" to be adsorption compounds of lignins and proteins.

Evidence for regarding humus as a single complex was obtained by W. McLean⁵⁷ from a study of the attack on soil organic matter by hydrogen peroxide. Whilst it is undoubtedly true that 6% hydrogen peroxide, originally proposed for differentiating humified from non-humified or structural matter, has an appreciable attack on cellulose in the presence of soil, a weaker peroxide (1-2%) is without action on this substance. By studying the effect of hydrogen peroxide of varying strength on the carbon and nitrogen content of soils, it was found that two stages of oxidation could be distinguished. Starting with the most dilute solutions, a complex of constant carbon-nitrogen ratio is progressively oxidized. Above a certain strength of peroxide, varying somewhat for different soils, there is no further oxidation of nitrogenous matter, but a progressive decomposition of non-nitrogenous compounds or complexes. The course of the oxidation of a Welsh brown earth is shown graphically in *Fig. 10*. It will be seen that, even with very dilute peroxide, there is a considerable oxidation of carbon and nitrogen; but whilst the oxidation of carbon slowly increases after about 86% has been attacked, there is no further attack of nitrogen beyond the first stage of attack.

The material oxidized in the first stage, termed by McLean the *oxidizable complex*, accounts for 70 to 80% of the total carbon and nitrogen present, and is more readily oxidized in base-unsaturated than in base-saturated soils. It would appear to be identifiable with the lignin-humus complex and the protein of Waksman (*loc. cit.*). The non-nitrogenous organic matter oxidized in the second stage may represent cellulosic material which has not as yet undergone microbiological decomposition.

Whilst, according to Waksman's earlier ideas, the lignin-humus and the protein were regarded as distinct complexes, the one representing resistant material surviving microbiological decomposition and the other consisting mainly of altered microbial protoplasm, the constancy of the carbon-nitrogen ratio of the organic matter oxidized by weak

peroxide does imply some close association between these groups. The high resistance of humic nitrogenous compounds to attack by ammonifying organisms compared with that of known plant and animal proteins suggests that the nitrogen of the oxidizable complex may be built up in com-

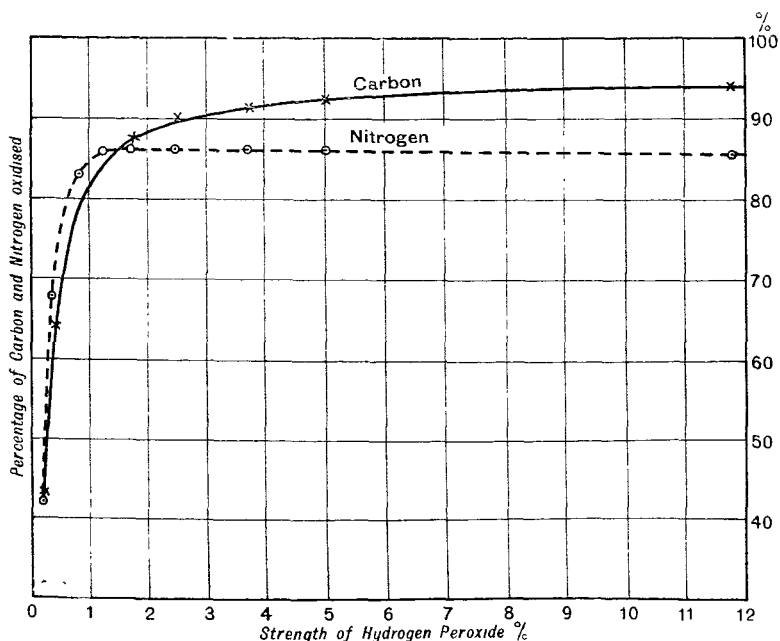


FIG. 10.—Oxidation of soil organic matter by hydrogen peroxide.

plexes such as the artificial "humus" prepared by L. C. Maillard (*loc. cit.*) from the condensation of carbohydrates and amino-acids.

More recently, S. A. Waksman and K. R. N. Iyer⁵⁸ have actually demonstrated the formation of a complex, from the combination of lignin and protein, which appears to be similar to soil humus in its properties. To this they apply the term *humus-nucleus*. There is good evidence for believing the humus of soils to be mainly of this character and to originate from the combination of plant lignins with

proteins. Evidence for its existence as a definite though complex compound was obtained by I. Siedlecky and B. Brunowski⁵⁹, who found all humus preparations to be crystalline and to give the same Debye-Scherrer diagram when examined by X-ray analysis. W. S. Gillam⁶⁰ found humic acid from three soil types to be chemically and physically similar.

It is necessary to emphasize the difference which appears to exist between plant lignin and the combined lignin of humus. Reference has already been made to McGeorge's evidence that soil lignin has a greater exchange capacity than plant lignin. It was considered originally by Waksman that lignin was resistant to biological decomposition. The rapid disappearance of plant residues under certain conditions, however, suggests its susceptibility to change. Further, M. Phillips, H. D. Weihe, and N. R. Smith⁶⁰ have shown that under certain conditions lignin may be as rapidly decomposed by soil organisms as celluloses and proteins. A. G. Norman⁶¹ found 40-50% of the lignin of oat straw to be removed in one year by aerobic decomposition at 28°C.

According to the foregoing ideas, the characteristic constituent of soil organic matter, humus, is a compound of altered lignin with proteins originating from plant proteins and the protoplasm of soil organisms, occurring as a single homogeneous ingredient, which, however, may be expected to have differing composition in different types of soils. The small amounts of celluloses and hemi-celluloses present must be regarded as fugitive in character.

As against the view that humus is a residual product of the decomposition or alteration of lignin, F. Y. Geltser⁶² considers that humic acid is formed from the products of the decomposition of plant residues by a distinct group of syntheses and that it is not necessarily related in constitution to the constituents of these residues. He postulates two types of humus, one characteristic of chernozems and cultivated soils, formed by the action of bacteria, and the other formed by fungal action occurring in peats and podzols. P. H.

Gallagher⁶³ distinguishes the "mobile" humus in podsoles as a separate type, differing from other types of humus by its solubility in oxalic acid and by its low nitrogen content.

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CHAPTER VIII

GENERAL PHYSICAL PROPERTIES OF SOILS

SOILS exhibit certain peculiarities in their physical properties by reason of the fact that they are essentially mixtures of mineral particles of varying size, together with closely associated colloidal clay and colloidal organic matter. The physical character and behaviour of a soil are governed by a number of circumstances, namely :—

(1) The nature and the size-distribution of the particles composing the non-colloidal skeleton or framework.

(2) The content of colloidal material.

(3) The character of the colloidal material, depending on (a) the relative proportions of organic and inorganic colloidal material; (b) the constitution of the inorganic colloidal material; and (c) the nature and content of the exchangeable bases present.

(4) The structure of the soil, *i.e.* the extent to which the primary particles of the soil are built up into aggregates, and the character of these aggregates or structural elements.

(5) The moisture content.

TRUE AND APPARENT DENSITY

It is necessary to distinguish, in the first place, between the true and the apparent density of a soil. Whilst the true density is an additive function of the densities of the soil constituents, the apparent density will vary according to the state of aggregation of the soil and the proportion of the apparent volume occupied by the interstitial spaces which are present even in the most compact soil.

The true density of a soil depends principally on the relative proportions of inorganic and organic matter present;

for, apart from certain heavy minerals, such as magnetite, which rarely occur in appreciable quantities, the densities of the inorganic constituents of the soil fall within a fairly narrow range. The following are the densities of the principal mineral ingredients of soils:—

Quartz	2.6-2.7	Amphiboles & Pyro-	
Orthoclase	2.54-2.57	xenes	2.9-3.6
Albite	2.605	Olivine	3.2-3.5
Oligoclase	2.65	Muscovite	2.76-3.1
Labradorite	2.68-2.71	Biotite	2.8-3.2
Anorthite	2.765	Chlorite	2.6-2.96
Apatite	3.16-3.22	Hæmatite	4.9-5.3
Magnetite	4.9-5.2	Limonite	3.6-4.0
		Clay	2.6-2.7

The density of soil organic matter varies from 1.2 to 1.7, but the figure is open to some doubt since the organic matter of ordinary soils cannot be isolated unchanged.

Since by far the greater part of the mineral matter of ordinary soils consists of quartz, feldspars, and clay, the density of the mineral soil free of organic matter is generally about 2.65. It is lowered by the presence of organic matter, and raised by the presence of oxides of iron such as magnetite, hæmatite, and limonite, and, to a smaller degree, by the presence of ferromagnesian minerals and micas. It is generally assumed that the density of a soil is an additive function of the densities of its constituents.

The true density of a soil has proved of comparatively little value for diagnostic purposes, since the presence of notable proportions of organic matter or hydrated ferric oxide is readily detected by other means. It must be admitted, however, that no attempts have been made to correlate density with soil constitution over the very wide range of soil which it is necessary to consider in modern investigations. If such correlations were worked out, the density might prove to have a certain significance and serve as an aid to diagnosis where other methods of investigation are impracticable.

Since the density of solid materials is generally obtained by methods depending on the use of liquids of known den-

sity, it follows that the density, and hence the specific volume, actually found will be affected by any surface reactions between the solid material and the liquid used. M. S. Anderson and S. Mattson¹ found that the specific volume of clays was highest in non-polar* liquids such as carbon-tetrachloride and lowest in polar liquids such as water. E. W. Russell² has shown that this may be attributed to the drawing together of the molecules of polar liquids in the electrostatic fields of force associated with exchangeable ions, and has deduced formulæ to express this effect quantitatively. According to these ideas, the true specific volume of a clay should be regarded as the value obtained in a non-polar liquid.

PORE-SPACE †

If a certain volume of a soil in its natural conditions be considered, it is evident that only a proportion of that volume is occupied by the soil material. The remainder consists of interstitial spaces which, under ordinary field conditions, are occupied partly by water and partly by air. The weight of unit volume of dry soil, including the interstitial spaces, gives the apparent density.

The relationship of the true density, d , and the apparent density, d_1 , to the pore-space will be apparent from the following considerations. If the percentage of pore or interstitial space be P , then the true volume of 100 c.c. of soil will be $100-P$, and the weight $(100-P)d$. The apparent density will therefore be $(100-P)d \div 100$, or $d-Pd/100$. The pore-space expressed in terms of true and apparent density is given by $P = 100(d-d_1)/d$.

*By a polar liquid is understood one in whose molecules the electrons are assymmetrically arranged round the nuclei, i.e., in which the electrical centre of gravity of the electrons is not coincident with the electrical centroid of the nuclei. In a non-polar liquid the distribution of the electrons round the nuclei of the molecules is symmetrical. In the former case the molecules will tend to orient themselves in an electrostatic field.

†The subject matter of this section has already appeared in Chapter II, but is given again here for the sake of completeness.

F. H. King³ gives the following figures for the percentage pore-space of typical soils :—

Sandy soil	32.5	Loamy clay	45.3
Loam	34.5	Clay loam	47.1
Heavy loam	44.1	Heavy clay	52.9

Such figures should be regarded only as giving orders of magnitude, for wide variations may occur in the same soil with changes in aggregation. Pore-space is increased by addition of organic matter, and may rise in grass soils to 60%, or more. Clay soils show wider variation in pore-space than sands.

Taking 50% as the pore-space under natural conditions, it is apparent that this does not represent the closest possible packing of the particles of which the soil is composed. With uniform spheres, the tightest packing gives a pore-space of about 26%. Where particles of different size are present and can pack into the interstices between the larger particles, the pore-space, theoretically, can be considerably reduced. It is evident that, with the particle-range of ordinary soils, the tightest possible packing would result in a pore-space very much less than 50%. The high figure actually obtained is due to the aggregation of particles into compound particles or crumbs. Any treatment which destroys the crumb structure and results in the soil particles behaving singly leads to a decrease in pore-space. This change may be brought about mechanically by trampling, or by the beating of heavy rain, and chemically by the action of certain substances known as deflocculants, of which sodium carbonate is the chief example. The change of a saline soil into an alkaline soil consequent on the removal of soluble sodium salts is accompanied by deflocculation, involving decrease in pore-space.

Pore-space generally decreases from the surface downwards, but may pass through a minimum in an illuvial horizon, particularly if there is compaction. Unfortunately, its determination under field conditions is beset with many difficulties.

It is clear that the pore-space in a soil varies both in dimensions and form. It may be regarded as forming a continuous three-dimensional network of channels and spaces of varying size. Just as we may speak of a particle-size distribution we may also speak of a pore-size distribution. Some writers have attempted to distinguish between capillary and non-capillary pore-space, the latter being considered as consisting of those voids that are occupied with air when the soil is moistened up to the capacity implied by the moisture equivalent. Such a distinction, although useful, is arbitrary and it is more correct to think of pore-space distribution as a continuous function. The form of this distribution has been investigated by determining the amount of moisture retained by the soil at varying suction pressures. F. Sekera⁴ has calculated the equivalent pore diameter for different suction forces as follows:—

Suction force (atm.) ...	0.03	0.1	0.3	1.0
Equivalent diameter ...	100 μ	30 μ	3 μ	10 μ

The equivalent diameter is thus inversely proportional to the suction pressure. The free capillaries in which water can circulate depend on the immobile film water. Coarse capillaries are defined as those greater than 30 μ , fine capillaries as those less than 3 μ .

TOTAL SURFACE OF SOILS

The subdivision of the soil material implied by its granular character involves a great development of surface, which is the more marked the finer is the texture of the soil. This is clear from the following considerations.

A cube having sides 1 cm. in length has a total surface of 6 cm². If, now, the cube be subdivided into millimetre cubes, the total surface will become 1000 \times 6(0.1²) cm². or 60 cm². The general relationship among particles of similar shape is that the specific surface, i.e., the surface per unit weight, is inversely proportional to the linear dimensions, i.e., in the case of spheres, inversely proportional to the radius.

It is possible, from a consideration of the mechanical composition curves of soils, to obtain an estimate of their specific surface.

The total surface of unit weight of a uniform soil fraction of diameter D , assuming the particles to be spherical, is equal to:—

Number of particles \times surface of each particle

$$= \frac{1}{vd} \times \pi D^2$$

[Where v =volume of each particle, d =density, for which the value 2.65 may be assumed, D =diameter of particles.]

$$= \frac{1}{\frac{\pi D^3}{6} \times 2.65} \times \pi D^2$$

$$= \frac{2.264}{D}$$

If 100 g. of soil consist of $p_1, p_2, p_3 \dots p_n$, per cent. of particles having diameters $D_1, D_2, D_3 \dots D_n$, respectively, the total surface is equal to

$$2.264 (p_1/D_1 + p_2/D_2 + p_3/D_3 + \dots p_n/D_n)$$

A measure of the total surface can be obtained graphically by the method of G. Krauss⁵ depending on the following argument.

Let the composition of the soil be set out in the form of a number of sectors, in which the angle of each sector is proportional to the percentage, p , of each fraction, and the radius proportional to $1/\sqrt[4]{v}$, the reciprocal of the fourth root of the settling-velocity.

Since the area of a sector, S , is proportional to the angle, and to the square of the radius,

$$S = k_1 p / \sqrt[4]{v} \quad (k_1 = \text{a constant})$$

But, from Stokes' Law, $D \propto \sqrt[4]{v}$,

$$\therefore S = k_2 p / D \quad (k_2 = \text{a constant})$$

The area of unit angle of each sector is thus inversely proportional to the diameter and, consequently, proportional to the total surface of the fraction represented by it; and the sum of the areas of the sectors is proportional to the total surface of the soil.

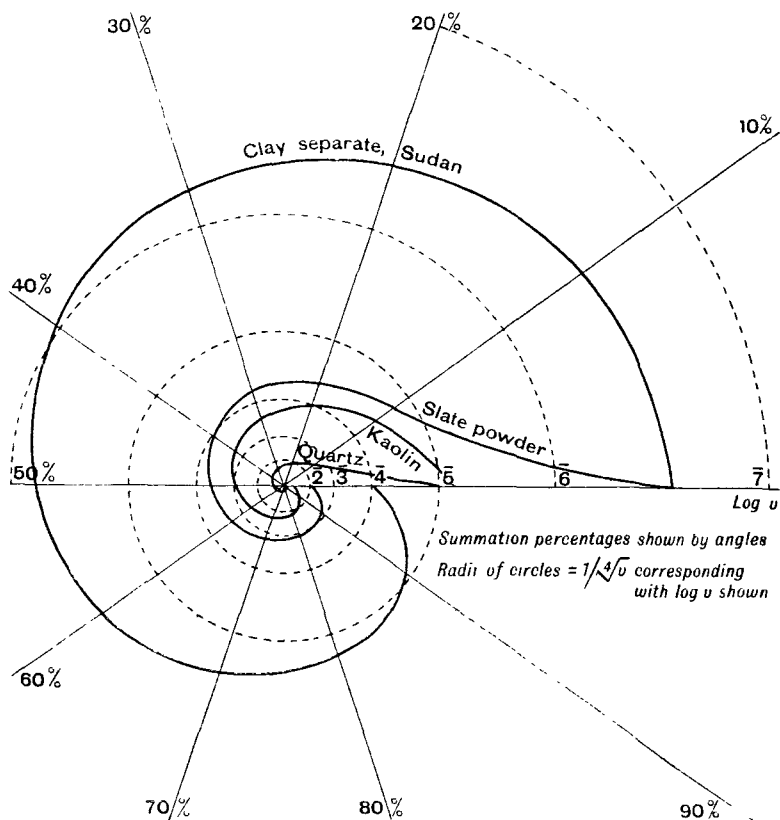


FIG. 11 —Total surface of certain materials.

In view of the smooth character of the mechanical composition curves of soils, it is sufficient to mark off at angular intervals, equivalent to 10%, radii proportional to the reciprocal of the fourth root of the corresponding settling

velocity, beginning with the lowest settling velocity. The area obtained by joining up the extremities of the radii is evaluated by means of a planimeter.

Curves drawn in this manner are shown in *Figs. 11 and 12*. The data are taken from the mechanical composition curves shown in *Figs. 1 and 2*.

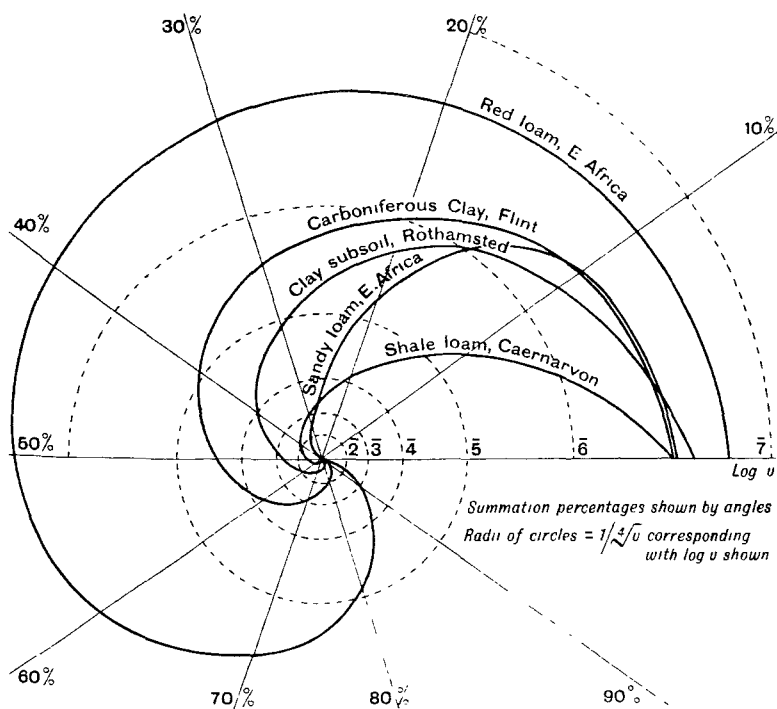


FIG. 12.—Total surface of certain soils.

The areas in square centimetres on the scale used and the estimated surfaces are shown in Table XIV. The latter figures are calculated on the assumption that the total surface per gram of uniform spherical particles, 0.002 mm. in diameter, is $2.264/0.0002 = 11,320$ square centimetres, and

that such particles have a settling-velocity equivalent to 10 cm. in 8 hours.

Inspection of the curves will show at once the small total surface possessed by mechanically comminuted materials such as slate powder and quartz powder, even although they contain very little coarse material. The small contribution of the coarser fractions to the total surface is also evident.

TABLE XIV.—TOTAL SURFACE OF TYPICAL MATERIALS

	Area included by curve sq cm.	Estimated surface, square cm. per gram.
Quartz powder	1.16	1913
Kaolin	7.80	12860
Slate powder	15.87	26130
Shaly light loam, Caernarvon...	18.45	30400
Sandy red loam, East Africa ...	36.97	60890
Clay subsoil, Rothamsted ...	43.48	71690
Raw Carboniferous clay, Flint	60.31	99350
Clay separate, Sudan ...	118.5	195200
Heavy red loam, East Africa ...	164.4	271800
Uniform fraction, 0.002 mm. diameter (calculated) ...	6.86	11320

The estimates thus obtained are probably no measure of the actual specific surface of the soils to which they refer, since under natural conditions a large proportion of the colloidal material, mainly responsible for these large figures, is probably built up into loose structures that become broken down in the operations of analysis. The values obtained may, however, serve a useful purpose in giving a comparative view of the degree of dispersion of which the specific surface is a measure.

From measurements of hygroscopicity, E. A. Mitscherlich⁶ obtained values for the specific surface, varying from 138 cm.² for fine sand to 96,670 cm.² for a clay from Java. These are now generally agreed to be over-estimates.

HEAT RELATIONSHIPS OF SOILS

The temperature of the soil is closely related to the temperature of the air. But, whilst the mean temperature of the soil throughout the year approximates very closely to the mean temperature of the air, the seasonal and diurnal variations show different courses according to the depth below the surface. Below a certain depth, the temperature of the subsoil is no longer affected by seasonal and diurnal changes and shows the ordinary increase with depth due to the influence of the earth's internal heat.

The response of the soil to additions or losses of heat in the form of radiation depends mainly on its specific heat, but also to some extent on losses of heat through vaporization from wet soil. Whilst the specific heat of dry soil shows a certain amount of variation, far greater variations are due to changes in moisture content, owing to the high specific heat of water. The effect of varying moisture contents on the specific heat of soils is illustrated by the data from E. A. Mitscherlich⁷ in Table XV.

TABLE XV.—VOLUME SPECIFIC HEAT (CALORIES PER C.C.) OF SOILS WITH VARYING MOISTURE CONTENTS (MITSCHERLICH)

Soil		Volume specific heat in calories per c. c. at varying degrees of saturation		
		Dry	50% Saturated	Saturated
Sand	...	0.302	0.510	0.717
Humus	...	0.148	0.525	0.902
Clay	...	0.240	0.532	0.823

In considering the specific heat of soils, it is generally desirable to express it on a volume rather than on a weight basis. From the point of view of field conditions, this leads to a truer estimate of the response of the soil to gains or losses by radiation than that obtained by the ordinary method of expression.

Soils that are habitually moist respond more slowly to the heating effect of solar radiation than dry well-drained soils. And thus, in the spring, the beginning of active plant growth takes place earliest in the driest soils.

The character of the diurnal variations in soil temperature is seen from the following data obtained by Mutterich^s in a sandy soil in Eberswald, Germany, in June, 1889. (Table XVI.)

TABLE XVI.—AIR TEMPERATURE, AND SOIL TEMPERATURE AT VARYING DEPTHS (MUTTERICH)

Time	Temperature °C.				
	Air	Surface	15 cm. depth	30 cm. depth	60 cm depth
12 midnight	13.80	16.71	19.42	17.90	15.88
2 a.m. ...	12.90	15.59	18.42	17.59	15.91
4 a.m. ...	12.53	15.14	17.84	17.33	15.91
6 a.m. ...	14.68	15.89	17.35	17.03	15.92
8 a.m. ...	17.99	17.54	17.52	16.75	15.91
10 a.m. ...	21.05	22.65	18.72	16.59	15.89
12 noon ...	21.97	25.00	20.52	16.64	15.84
2 p.m. ...	22.61	26.37	22.08	17.00	15.80
4 p.m. ...	22.38	25.89	22.91	17.37	15.77
6 p.m. ...	21.24	22.32	22.64	17.71	15.75
8 p.m. ...	17.55	19.76	21.65	17.99	15.77
10 p.m. ...	14.80	17.81	20.53	18.06	15.88
Mean ...	17.79	20.06	19.97	17.33	15.85

The actual temperatures observed under other conditions will vary according to the course of the air temperature, the intensity of the solar radiation during the day, and the rate of loss by radiation during the night: yet the data in the above table illustrate the main features of the temperature changes in the soil. In sunny weather, the temperature of the actual surface of bare soil reaches a higher maximum than the air. Indeed, surface temperatures as high as 85°C have been reported from the tropics. Below the surface, the

Eberswald data show that, with increase of depth, the amplitude of the diurnal temperature changes decreases, whilst the maxima and minima of the curve show an increasing lag behind the maxima and minima on the air temperature curve. Thus, whilst in the air, the maximum is at 2 p.m., and the minimum at 4 a.m., at 15 cm., the maximum is at 4 p.m. and the minimum at 6 a.m., and at 60 cm., the maximum is at 6 a.m. and the minimum at 6 p.m. The corresponding amplitudes are 7.81° , 5.56° , and 0.17° , respectively.

Under a cover of grass vegetation, the amplitude of the temperature changes at the surface is less than in bare soil, but there is a tendency for the minimum to be below that in the air. Still smaller variations occur under forest. But in every case there is the same tendency for amplitude to decrease with depth and for the changes to lag behind those at the surface.

I. de V. Malherbe⁹ found in S. Africa that where the annual air temperature amplitude was $66-70^{\circ}\text{F.}$, the corresponding figures in the soil were at 3", 58.6° , at 6", 39.2° , at 12", 28.8° , and 24", 24.6° . The mean daily range at 3" decreased from 23.4° in January to 3° in July. The mean range at 24" was $0.7-2^{\circ}$. Summer rain lowers temperature at 3" by about 15° .

Situation and aspect affect the temperature of the soil. For each 300 feet increase in altitude there is a fall of approximately 1°F in air temperature, which is reflected also in the soil temperature. South slopes, in the Northern Hemisphere, are warmer than north slopes since they receive more intense isolation. (See also p. 109.)

Colour affects soil temperature. Dark-coloured and red soils absorb solar radiation better than light-coloured soils. Wollny, comparing the temperature, at 4 inch depths, of soils covered with black and white material, respectively, found differences of nearly 6°C in favour of the former.

The seasonal changes in temperature show a similar tendency. With increase in depth, the difference in mean

temperature between summer and winter becomes smaller and finally disappears. From A. A. Rambaut's¹⁰ observations at Oxford, it appears that, under a grass vegetation, the temperature at 10 feet varies from a minimum of about 45.5°F in March to a maximum of 56°F in September; at 6 feet, the range is from rather less than 44°F in February to 59°F in August; whilst at 6 inches, the range is from 38.5°F in February to 66.5°F in July. It is thus evident that the temperature of the soil lags markedly behind that of the air, and that lag increases and amplitude decreases with the depth.

Whilst variations in soil temperature are due mainly to the seasonal and diurnal changes in solar radiation, minor fluctuations are caused by other circumstances. Clouds check the loss of heat from the soil by radiation during night and hinder access of heat by radiation during day. Drying winds blowing over moist soils cause a lowering of temperature corresponding with the latent heat required for the evaporation of moisture. Precipitation on cold soil from moist warm air results in gains of heat.

The freezing of soils takes place normally from the surface downwards. In regions with perpetually frozen subsoil there is thus at the onset of winter a zone generally saturated with liquid moisture lying between the frozen surface and the frozen subsoil. In Britain where the temperature at depth tends to approximate to the mean annual temperature, about 50°F., frost rarely penetrates more than a foot or so. Even in the more continental climate of France according to H. Geslin¹², the depth of freezing rarely reaches one metre. V. Novak¹³ in Czechoslovakia found that penetration was less under grass. Compaction increases penetration. Whilst in arable, penetration was rarely more than 80 cm., under field roads it reached 100 cm. and under town roads, 160 cm. Geslin (*loc. cit.*) also states that compaction increases thermal conductivity, and presumably the rate of penetration of frost. Free water, i.e., the water in the larger capillaries, freezes first and the ice crystals thus formed grow at the expense of the moisture in the finer capillaries.

The "heaving" effect of frost depends on the state of compaction and on the moisture content. A snow cover generally stabilizes temperature and hinders penetration of frost. Whilst thawing generally takes place from the surface, according to R. K. Schofield it may take place from below when snow falls or where an initially severe frost moderates.

SHRINKAGE AND EXPANSION

Anyone familiar with a clay country will have noticed the cracking of the surface of the soil during drought. The shrinkage on drying which leads to this cracking is most marked in the heaviest clays. The fissures thus opened often extend several feet into the soil and result in a further intensification of the drying-out process. Material from the surface sometimes falls into the fissures and it has been shown by H. Greene¹¹ that, in the Sudan Gezira, this leads to a considerable circulation of soil material.

Shrinkage on drying is also observed in highly organic soils. The drying-out consequent on the drainage of peat soils is accompanied by marked contraction, so that the surface may be appreciably lowered.

Under laboratory conditions shrinkage is studied by moulding soil with water into a plastic paste and measuring the volume occupied at varying moisture contents during drying. In such a paste, the volume is represented by the soil and water only, for, by the method of preparation, interstitial air spaces, such as occur under natural conditions, are excluded. The curve connecting volume with moisture content is at first linear, the decrease in volume corresponding exactly with the loss in moisture. As the paste becomes drier, however, the curve begins to depart from the initial straight line and the diminution in volume lags behind the loss in moisture. At this point interstitial air spaces make their appearance and there is a change in colour towards that of the dry soil. The shrinkage that occurs after the linear relationship has been departed from is termed *residual shrinkage*.

W. B. Haines¹⁴ has determined the residual shrinkage of materials formed into plastic blocks. His results are shown in Table XVII.

TABLE XVII. — SHRINKAGE OF PLASTIC BLOCKS AND CLAYS (HAINES)

Soil		Total Shrinkage %	Residual Shrinkage %	Clay % (log v = 4)	Ignition Loss %
Clay separate	...	130.0	8.6	90.5	9.5
Kaolin	...	30.0	nil	52.8	12.4
Sudan clay	...	67.5	7.6	42.3	11.4
Clay subsoil	...	34.0	2.0	33.8	9.6
Harpenden common	...	37.5	10.3	25.5	10.5
Rothamsted loam	...	21.0	2.2	14.8	8.3
Sandy soil...	...	9.5	2.6	5.3	8.3
Peat soil	...	85.5	18.2	—	27.0

Whilst the total shrinkage represents roughly the water holding capacity of each material, the residual shrinkage appears to be connected with the presence of colloidal gel material present. It varies from nil in the case of kaolin to 18.2% in the case of a peat soil. In the case of kaolin or any other gel-free powder, shrinkage corresponds with water loss until the grains come into contact, after which no further shrinkage can occur. But where gel material is present, it is interposed between the mineral grains and opposes a resistance to shrinkage in the later stages of drying. The property of residual shrinkage can be conferred on non-colloidal powders such as kaolin by admixture of colloidal material such as gelatin.

The results obtained in the laboratory are only partially representative of field conditions, where, even in wet soils, a certain proportion of air spaces is always present above ground-water level. The laboratory conditions are most closely simulated by the individual "clods," which, in varying proportions, are always present in clay soils.

The shrinkage of soils on drying produces certain characteristic structures such as prismatic, columnar, and nuciform, which are often of considerable diagnostic value in the study of profiles. (See p. 249.)

Swelling takes place when the moisture content of dry soil is increased. The swelling curve, however, is not coincident with the shrinking curve. At the same moisture content the volume shown on the swelling curve is greater. D. P. Sideri¹⁵ distinguishes between (a) capillary or intermicellar imbibition in which water enters the spaces between the micellar structures and (b) intramicellar swelling, in which the actual micelles increase in volume.

PLASTICITY

Plasticity may be defined as the ability of a material to change shape continuously under the influence of an applied stress, and to retain the impressed shape on the removal of the stress. The exhibition of this property by soils is dependent on the presence of certain proportions of water. A. Atterberg¹⁶ has distinguished an *upper* and a *lower plastic limit*. The upper limit of plasticity of a soil is the point at which the soil-water paste is just fluid, i.e., the point at which it fails to retain the shape impressed on it by an applied force. The lower limit of plasticity is the point at which cylindrical portions of a soil-water paste crumble down on being rolled, i.e., the point at which the paste is unable to change shape continuously under the influence of an applied force. The difference between the moisture contents, calculated on the dry soil, at the upper and lower limits is termed the *plasticity number*. Since soils containing moisture in excess of the lower limit are plastic, this point represents the highest moisture content at which a soil can be cultivated without injury to tilth.

In Table XVIII, the plasticity data obtained by Atterberg for some typical Swedish soils are given.

TABLE XVIII. — PLASTICITY DATA FOR SOME TYPICAL SOILS (ATTERBERG)

Soil		Upper Plastic Limit ° Water	Lower Plastic Limit ° Water	Plasticity Number
<i>Highly Plastic Soils—</i>				
Silurian clay	...	67	40	27
Ancylus clay	...	57	30	27
Glacial clay	...	51	26	25
<i>Moderately Plastic Soils—</i>				
Fresh-water clay	...	52	37	15
Arable soil	...	42	30	12
Glacial clay	...	32	25	7
<i>Feebly Plastic Soils—</i>				
Arable soil	...	64	58	6
" "	...	33	28	5
" "	...	22	18	4

Plasticity is associated with the presence, in soils and clays, of inorganic colloidal material. The property can be exhibited also by finely ground lamellar minerals such as mica and biotite. It is more strongly developed in soils with siliceous clay fractions than in soils whose clay fractions contain notable proportions of sesquioxides.

COHESION

Cohesion is closely associated with plasticity, for plastic soils are cohesive and set into hard clods on drying. It is markedly affected by changes in moisture content and, in heavy and medium-textured soils, increases as the soil dries. The intractable clods formed in the drying out of heavy clay soils are familiar to cultivators. With extremely light sands, however, cohesion may pass through a maximum with decreasing water content and then decrease as complete dryness is approached. This is exemplified by the looseness of sandy soils when completely dry.

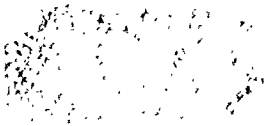
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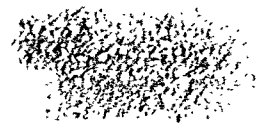
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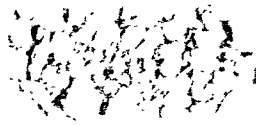
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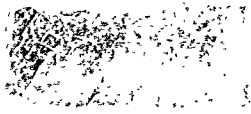
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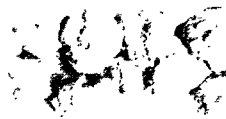
Fragmentary



Mulch



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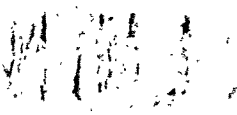
Pitsoadite



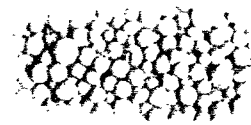
Columnar



Platy



Shot



Orbslum (Cemented)



[Photo C. E. Kellogg
[To face page 249.

SOME TYPES OF SOIL STRUCTURE

S. Johansson¹⁷, using a method devised by Atterberg for the measurement of cohesion, has constructed curves connecting cohesion with moisture content for typical soils. The curves appear to be composite in character, but the work of W. B. Haines¹⁸ throws some doubt on the discontinuous character of the cohesion-moisture relationship.

SOIL STRUCTURE

The ability of soils to assume a condition of aggregation, thereby acquiring a definite structure, has been already mentioned. We shall now discuss the problem with more close attention.

In the first place we may distinguish the single-grain from the aggregated, granular, or crumb structure, and it is desirable to direct attention at once to a possibility of confusion. Whilst structure is generally regarded as a consequence of the aggregation of the primary particles of the soil into compound aggregates, there is a series of formations, also termed structures, in which the soil is predominantly in the single-grain structure. Such are the laminated and pulverulent structures shown by A horizons of podsoles, and the columnar and prismatic structures shown by the B horizons of a group of soils termed solonetz (see Chapter XIII). Examples of these structures are shown in *Plate III*.

Columnar and prismatic structures are actually the result of the shrinkage consequent on the drying out of highly dispersed clays, and it is of interest to note that the structural units thus formed appear to be permanent over recurring cycles of moistening and desiccation.

Most of the investigations on structure that have been made during recent years, however, are concerned with structure in its more usual significance, namely, the aggregation of the soil into compound granular particles. Whilst it is generally recognized that the maintenance of the granular or crumb structure is desirable from the point of view of plant growth, considerable difficulty has been experienced in

explaining the mechanism of crumb formation and in finding means of expressing it quantitatively.

Growing plants have an effect on soil structure partly through their residues, including organic matter sloughed off from growing roots, and partly as a direct result of root action. This may be seen in the soil in which seedlings have been raised in close array. I. P. Sarakhov¹⁹ considers that grasses favour stable structure, perennial ryegrass being the most effective in this respect. Lucerne is the best structure-former among the legumes. Maize is considered to have a bad effect on structure. The good effect of grass on structure is familiar to every farmer who has ploughed up old turf. After years in grass, even the heaviest clay soils acquire a good structure.

The microbial population of the soil has an effect on structure formation. T. C. Peele²⁰ attributes a binding action to the mucus produced by bacteria, e.g., those from pea nodules. The aggregates thus formed are water-stable. Addition of sucrose to the soil by stimulating microbial growth increases the percentage of water-stable aggregates. J. R. McHenry and M. B. Russell²¹ studied the effect of decomposition of untreated and hot-water extracted organic matter on aggregation. They found an initial increase in water-stable aggregates up to six days due to the decomposition products and microbial wastes. Then followed a breakdown and afterwards a further rise due to accumulation of decomposition products of the more resistant organic constituents. Investigations by J. P. Martin²² on a fungus of the *Cladosporium* group showed a marked aggregation of silt and clay partly due to substances produced by the fungus and partly to the binding effect of the fungal mycelium. In the case of an aerobic bacillus of the *B. subtilis-mesentericus* group, 80% of the aggregating effect was due to substances excreted. In the case of the bacillus a hemi-cellulose-like substance was primarily responsible but being readily attacked by bacteria and actinomyces, its aggregating effect is only fugitive in character. G. M. Browning

and F. M. Milan²³ found that the aggregation caused by the decomposition of organic materials added to the soil reached a maximum effect in 20-30 days and gradually became ineffective.

With regard to the mechanism of crumb formation, it is generally recognized that the colloidal constituents play an important part in facilitating aggregation. In this connexion it is necessary to emphasize the distinction between the aggregates formed by humus and those formed by clay as a cementing agent. Where the aggregation is mainly due to humus the structure is loose and spongy, a good example being the structure found in many old garden soils and in potting-moulds. This structure, for which there is no satisfactory English term, is termed by the German farmer "Bodengare," the underlying idea being that the soil is "puffed up." Indeed, earlier theorists have actually attributed this structure to the evolution of carbon dioxide within the soil.

Where clay is a cementing agent, the structure is less spongy in character and the individual aggregates tend to be of a clod-like character, the "shot" and "nut" structures of the American workers being examples (see *Plate III*). In most agricultural soils both clay and humus participate in crumb formation.

Different types of aggregation have been recognized. A. T. Tiulin²⁴ has distinguished true and false aggregates, the former held together by bivalent and trivalent cations and the latter by univalent cations or simple cohesion. A. Demolon and S. Hénin²⁵ draw a similar distinction, but regard the looser type of aggregation (*état motteux*) as formed under the influence of compression. The loose aggregates can be considered as temporary in character, owing their existence to the operations of cultivation, the action of frost and possibly to the effects of plant roots. The other type of aggregates appears to be more permanent. We may regard it as due to the presence of colloidal material having exchangeable cations.

E. W. Russell^{2b} has put forward the hypothesis that the cohesion, leading to crumb formation, exhibited at low moisture contents is due to the effect on clay particles of oriented molecules of water. The hypothesis applies equally to other polar liquids. In a dilute clay suspension each particle is surrounded by water molecules oriented along the lines of force of its electrostatic field. Free ions in the dispersion medium are similarly surrounded by oriented water molecules. If the suspension becomes concentrated

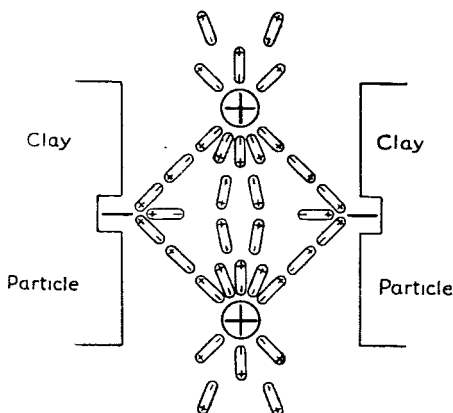


FIG. 13.—Orientation of water molecules between two clay particles.
(RUSSELL.)

there will be an increasing tendency for water molecules to become oriented as shown in *Fig. 13*, where the negatively charged surfaces of two clay particles are shown linked through a pair of cations. The linkage system thus consists of: clay particle—oriented water molecules—cation—oriented water molecules—clay particle.

Crumb formation thus depends (1) on the presence of the double layer consisting of an inner shell of anions and an outer shell of cations, of which some are dissociated, and (2) on the presence of a polar dispersion medium. It cannot be expected with materials having no base exchange properties

nor by the desiccation of suspensions in non-polar liquids such as carbon tetrachloride.

Whilst it would appear to be exceedingly difficult to obtain a quantitative measure of the loose aggregation of the soil, apart from pore-space, which will be the greater, the more the soil is in this state, it might appear feasible to obtain a measure of the extent to which the soil is formed into true aggregates.

The specification and measurement of soil structure is a problem that presents many difficulties, for, whilst it is not difficult to be aware of the existence of structure, its precise expression is less easy. The solution of the problem has been attempted along a number of lines.

(1) There are many methods designed to express the aggregate analysis of soils, i.e., the relative proportions of the different sized crumbs present. Essentially these methods are similar to mechanical analysis without dispersion. The inherent difficulty in all the methods proposed is that in treating the soil, either by sieving or by sedimentation methods, there is an unavoidable interference with the natural structure, so that comparable results can be obtained only by a rigid prescription of the technique to be followed. A number of methods depend on dry sieving. There is also a variety of wet sieving methods, of which that of A. F. Tiulin²⁴ is most widely used. The soil, after a preliminary wetting, is placed on a nest of sieves which are dipped 30 times in water. Whilst all the methods proposed have a certain value, they are essentially conventional, and until some general agreement is reached as to the precise details of the technique, the existing methods must be regarded as provisional. A. Demolon and S. Hénin²⁵ reject the use of water alone in aggregate analysis and propose the use of 0.1% calcium nitrate solution, by which, it is held, the original state of aggregation is maintained.

(2) Aggregate analysis, however carried out, does not give significant information unless the results of mechanical analysis with complete dispersion are available for compari-

son. The somewhat drastic measures used in this preliminary dispersion are evidence of the stability of the aggregates that are broken down. P. Vageler and F. Alten²⁷ have proposed to express soil structure by a single factor, the *structure factor*, which is simply the ratio of the difference between the total clay and the clay obtained by water dispersion expressed as a percentage of the total clay obtained by complete dispersion. With poor structural development will be a tendency for the ratio to approach zero. A measure of structure is also obtained where mechanical analysis is carried out with a simple water dispersion, the so-called aggregate analysis. The difficulty lies in prescribing the stage to which dispersion shall be carried. There is no evidence that the dispersion secured in the International B method, for example, represents more than an arbitrary stage in dispersion.

(3) The problem of soil structure may be approached from a different angle by studying the pore-space distribution. A simple expression of this is the division of the total pore-space into non-capillary pore-space (macro-porosity) and capillary pore-space (micro-porosity). A more exact expression may be given by an interpretation of the curves connecting moisture content with suction pressure. The form of the curve connecting pF with moisture content can throw light on the distribution of pore-spaces in the soil. The relationship is complicated by hysteresis effects and by swelling and shrinkage of colloidal material with changing moisture content.

An important aspect of structure is the stability of aggregates. It is obvious that the loose or false aggregates have slight stability. D. G. Vilensky²⁸ contrasts aqueous stability, the property whereby the soil disaggregates under the influence of water, and mechanical stability whereby resistance is opposed to disaggregation by mechanical means. It is suggested that both types of stability depend on the moisture content of the soil at the moment of formation of aggregates. This, of course, refers only to an individual

soil, for the stability of aggregates, compared among different soils, depends on the nature of the colloidal complex and the exchangeable cations. It is commonly supposed that calcium-saturated colloids give the most stable aggregates, an impression which is favoured by the known ameliorative effect of lime on the structure of soils. Recent work has shown that base-unsaturation does not necessarily imply bad structure. Thus J. F. Lutz²⁹ considers that so far as flocculation and low hydration are concerned, hydrogen clays should possess better physical condition than calcium clays. H. E. Meyers³⁰ finds that calcium was no more effective than hydrogen in forming stable aggregates. The good effect of lime is held to be due to its action on the organic matter status of the soil.

TYPES OF STRUCTURE

Apart from the desirability of being able to give a quantitative expression of soil structure, it is very desirable for many purposes, particularly for soil survey, to have methods of describing soil structure as one element in soil morphology. Many methods have been proposed, the majority based on the work of S. A. Zakharov³¹, whose three fundamental types are (1) cubicular, (2) prismatic, and (3) plate-like. A development of Zakharov's system is that of the American Soil Survey Association. Two main types are distinguished, namely, (1) *simple structures*, in which the particles are unaggregated and natural cleavage planes are not visible, and (2) *compound structures*, in which aggregation with visible cleavage planes is evident. The simple structures are subdivided into (a) simple-grained, (b) amorphous, (c) massive, i.e., particles consolidated to a uniform mass, (d) pulverulent, and (e) puddled. The compound structures are divided into the three types cuboidal, prismatic, and platy, following Zakharov. The cuboidal types are further subdivided into the granular and fragmental, the former with poorly defined edges and surfaces and the latter with well-defined edges and surfaces. Further subdivision

of these sub-types and of the columnar and platy types is on the basis of the size of the aggregates. A convenient distinction among the cuboidal types is between the rounded and the polyhedral aggregates. The rounded aggregates or crumbs may be distinguished by their size and resistance to crushing. Thus one may have coarse soft crumb, medium soft crumb, coarse hard crumb, etc. Hard crumb structure is generally termed granular, as in the chernozems.

In describing soil structure it is also necessary to note porosity (size and disposition of pores) and compaction. Attention must also be given to the presence of coatings, e.g., of humus or salts on the surfaces of the structural elements. W. Kubiena³² regards soils as built up of fabric units, which may be crystal fragments, raw humus particles, films, coagels, bridge or cavity-filling formations, etc. He distinguishes skeletal and plasmatic elements. The following types of aggregates are recognized:—

Porphyropeptic. Uncoated minerals in an almost massive or at least only finely cracked ground mass which easily separates. This structure occurs in laterites.

Porphyropeptic. Minerals always covered by colloid coatings or thick films, with the appearance of being embedded in a ground mass. Characteristic of Mediterranean red earths.

Intertextic. Uncoated minerals bound by friable colloid bridges or in a ground mass with many cavities, as in the chernozems.

Plectoamictic. Mineral grains with colloidal coating bound by colloid bridges or in a cavernous ground mass.

Chlamydomorphous. Each grain with a colloid coating, bound together in loose aggregates, as in the B-horizon material of podsoles.

Agglomeratic. Grains uncoated or with loosely-attached friable coatings. Plasmatic material present as aggregates in the pore-spaces. Aggregation undeveloped or only slightly developed.

“*Bleicherdegefüge*.” Uncoated grains, as in bleached horizons of podsoils, with independent raw-humus agglomerates. No aggregate formation.

The structure of soil as viewed under field conditions, particularly in the examination of soil profiles, is an important aid to the diagnosis of soil characters. It should not, however, be given undue weight and regarded as other than an outward manifestation of the essential constitution and properties of the soil. And, therefore, whilst structure may be of the greatest utility for the diagnosis of soils in the field, it would be unwise to use it as an actual basis of classification. For example, soils with a certain type of structure have been termed “solonetz” by the Russian workers. At a later stage it was found that these soils were characterized by having sodium as the predominant cation in the absorbing complex and a hyperalkaline reaction. C. F. Shaw and W. P. Kelley⁴³ have encountered examples in Utah and California, and J. H. Ellis and O. G. Caldwell⁴¹ examples in Alberta, of soils with solonetz type of structure, but with an entirely different type of cation complex. Which is the more significant, the chemical constitution or the visible structure? In the writer’s opinion, the constitution of the soil as revealed by chemical examination should undoubtedly have priority of importance.

COLOUR

The colour of the soil, especially the changes in colour through the horizons of the soil profile, is one of the most important aids to the recognition and description of the different genetic groups.

In the first place, it should be remarked that there is always a progressive lightening in colour as a soil dries out. The change may be attributed to the development of air spaces in the soil crumbs or in the colloidal coating of the coarse particles and, finally, to the partial dehydration of the colloidal material itself. Until a soil has dried down to the point at which air spaces occur there is, thus, no change

in colour. In laboratory experiments, the beginning of colour change is found to correspond with the point at which there is a change in the direction of the curve connecting volume with moisture content. When the soil has reached the stage of desiccation at which only hygroscopic moisture is present there is no further change in colour.

Broadly speaking, it may be said that the most marked differences between wet and dry soil colours are found in soils containing high proportions of colloidal material. For example, black peaty soils may become light grey when dry.

The colours of moist soils are generally more vivid and strongly contrasted than those of dry soils. Soils which stand out sharply from each other under moist field conditions are much less distinct when they become dry laboratory samples. It is therefore preferable to use the colour of the moist soil for descriptive purposes where possible. The drying to which soils are subjected in the preparation of laboratory samples appears to involve colour changes which are not readily reversible on re-moistening.

The colour of the moist soil is governed principally by two constituents, namely, the colloidal organic matter and the colloidal clay. Generally speaking, organic matter confers the dark colour on soils. Among soils of the same group, the colour becomes darker with increasing proportions of this constituent. It should be noted that the effect of organic matter is more marked in sandy than in silty or clay soils. A coarse sand with 10% of organic matter may be nearly black when moist, whilst the same proportion of organic matter in a clay soil would have only a slight effect on the mineral colour.

The darkening effect of organic matter varies among the great soil groups. In the chernozems, the rendzinas, and certain tropical and sub-tropical soils with high lime-status, the humification of plant residues appears to produce a very dark-coloured humus. On the other hand, in the red soils of the humid tropics, the humus appears to be lighter in colour. It may be, however, that its colour is masked by

the highly coloured clay colloids of such soils. In the bleached horizon of podsol soils the organic matter would appear to be only slightly coloured. That differences exist in the colour of humus is only to be expected from the diversity of the processes whereby it is produced.

Except in highly organic soils, the colour is governed mainly by the soil mineral matter and, in particular, by the colloidal clay. In studying soil colour, it is generally convenient to destroy the humus by boiling with sufficient 6% hydrogen peroxide, whereby the true mineral colour may be observed. The removal of even small proportions of organic matter by this treatment results in an appreciable "brightening" of colour, whilst in the case of dark-coloured organic soils the colour change is frequently remarkable.

Considering the mineral colour of soils, we may say at the outset that the unweathered minerals of the soil contribute but slightly to soil colour, which is conferred usually by the inorganic weathering-complex. On the other hand, H. E. Annett³⁵ has shown that finely divided magnetite is largely responsible for the dark colour of certain black cotton soils in India. Blue and green colours in subsoils may be attributed to the presence of ferrous compounds such as pyrites, marcasite, vivianite, and glauconite.

The mineral colour is mainly due to compounds of iron, and to a less extent, of manganese. Yellow, brown, and red colours are due to the presence of ferric oxides with varying degrees of hydration. Broadly speaking, red colours are associated with lower degree of hydration, such as are commonly encountered in tropical soils. Some effect on colour must, however, be attributed to the stage of aggregation of the hydrate of ferric oxide present. The effect of a coloured constituent is more evident in sandy soils than in soils of heavier texture. On account of the low specific surfaces of such soils, comparatively small proportions of hydrated ferric oxide are sufficient to confer a marked red or brown colour. The strong colours of certain soils of the Trias and Old Red

Sandstone formations and of certain desert soils do not therefore necessarily denote high proportions of ferric oxide. The most vivid red colours are found in soils of the humid tropics. Red colours may also occur in desert soils. High temperatures are apparently necessary for their development, which may be due to decomposition of the clay complex.

Soil colour is markedly influenced by the constitution of the clay complex. Generally speaking, soils in which the weathering-complex has originated in the presence of notable proportions of calcium compounds, such as the chernozems, rendzinas, chestnut earths, and grey desert soils, show, so far as the mineral portion of the soil is concerned, grey or greyish-brown colours. The clay complex of such soils is rich in silica, and it may be presumed that sesquioxides exist only in combination with silica and not in the free state.

Grey colours occur in the A horizons of podsol profiles, due to the removal of ferric oxide by acid percolating waters. The grey colour is often only evident after removal of humus by peroxide treatment.

Grey colours are found also in the A horizons of soloti or degraded alkali soils. In such soils, the leaching out of the sodium soil in the absence of calcium carbonate leads to a decomposition of the clay complex and an eluviation of sesquioxides, leaving an A horizon rich in residual silicic acid.

There is also a large group of soils in which, although notable proportions of iron are present, grey colours prevail owing to reduction to ferrous compounds. These are the soils of marshes and bottoms where free aeration is prevented by excess of moisture. Such soils occur not only in cool and temperate regions, but also in the tropics, where the grey mineral colour is frequently masked by dark organic matter.

In considering the colour of soils it is important to decide whether the colour reflects recent pedogenic process or

whether it is simply a rock colour. The red colour of the soils of the English Trias and Old Red Sandstone must be attributed to the parent rock and not to the operation of contemporary processes. It represents rather the result of the weathering processes of Triassic and Devonian times.

SPECIFICATION OF SOIL COLOUR

The accurate specification of the colour of soil is a matter of considerable difficulty both on account of the great subjective errors to which an estimate of colour is liable and also on account of the lack of any generally recognized scale of colours.

Numerous attempts have been made to arrive at a system of recording soil colours. The soil colours may be matched with a colour of known specification in a colour atlas such as those of Ridgway or Ostwald; or, alternatively, they may be matched with composite colours, obtained by the combination, in varying proportions, of standard colours. The method employed by J. G. Hutton³⁶ may serve as an example.

The desired soil colour was obtained by combination, in a rapidly rotating disc, of varying proportions of four standard colours, namely,

Neutral 9	...	...	...	...	...	White
Neutral 1	...	...	...	...	...	Black
Red 4/9	...	...	...	...	...	Red
Yellow 8/8	...	...	...	...	...	Yellow

The colours were obtained from the Munsell Colour Co., of Baltimore, Md., and were accurately specified by the U.S. Bureau of Standards.

A selection from Hutton's data for the colour value of some typical soils is shown in Table XIX.

TABLE XIX.—COLOUR VALUE OF TYPICAL SOILS (HUTTON)

Soil Colour Name	White %	Black %	Yellow %	Red %
Grey	22.0	60.0	11.0	7.0
Dark grey	16.0	67.0	9.0	8.0
Yellow	11.5	19.0	45.5	24.0
Greyish-brown	14.0	50.0	22.0	14.0
Reddish-brown	7.0	44.0	18.5	30.5
Dark reddish-brown	3.0	72.5	10.5	14.0
Light brown	10.0	59.0	18.0	13.0
Dark brown	4.0	73.0	12.0	11.0
Dark greyish-brown	9.0	73.0	11.0	7.0
Red	3.0	35.0	20.0	42.0
Dark red	0.0	70.0	7.0	23.0

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CHAPTER IX

WATER RELATIONSHIPS OF SOILS

RETENTION OF MOISTURE BY SOILS

SOIL, on account of its granular and colloidal character, is able to retain moisture received through rainfall or irrigation. This property is of the highest significance both in the control of the pedogenic processes and in the life of plants. The study of the moisture relationships of soils may therefore be considered to be the most important group of problems in soil physics.

These problems fall under the following headings:—

(1). The manner in which water is retained by soils and the quantitative expression of the differences in their behaviour in this respect.

(2). The movements of water in soils, including the distribution within the soil of water received by rainfall or irrigation, and the factors affecting losses by evaporation.

In the earlier literature the retention of water by soils was viewed as the adherence of water films to the soil particles or, alternatively, as comparable with the retention of water in capillary tubes of varying cross section. This approach proved unsatisfactory, and in order to show more precisely the nature of the physical forces involved, theoretical and experimental studies have been made of water retention and movement in the *ideal soil*,* which was imagined as consisting of uniform spheres in close (hexagonal) packing.

The ideal soil concept was largely developed by W. B. Haines¹, who showed that the interstitial spaces in a system

*The epithet is used in a purely philosophical sense, and does not imply excellence for the growth of plants.

of close-packed uniform spheres were of two types, namely, tetrahedral and rhomboidal, the former occurring at the centre of four adjacent spheres arranged as an equilateral pyramid and the latter occurring between a group of six adjacent spheres arranged in two parallel planes. The spaces are present in the proportion of two tetrahedral cells to each rhomboidal cell. At low moisture contents water is present as rings at the points of contact of adjacent spheres. With increasing moisture the rings become larger until their edges come into contact. At this stage, it is shown that 24% of the pore-space is occupied by water. Up to this stage the water is described as *pendular* water. With further increase in moisture the liquid phase now forms a continuous system. The air phase is similarly continuous. This is described as the beginning of the *funicular* stage. With further increase in moisture the pores become full of water, and this is described as the capillary stage. It is shown that these transitions are not continuous but that discontinuous redistributions occur.

When the moisture decreases from saturation similar discontinuous changes in moisture distribution occur until the pendular stage is reached. Both in moistening and drying the moisture content is controlled by pressure deficiency, but different moisture contents can be associated with a given pressure deficiency, depending on the previous course of events.

In actual soils the shape and distribution of interstitial spaces will differ considerably from that in an ideal soil of uniform closely packed spheres, but the general relationships between moisture content and pressure deficiency with increasing and decreasing moisture content are not dissimilar.

Whilst conditions approximating to those in the "ideal soil" can scarcely ever be realized in actual soils, the treatment of soil moisture from this standpoint marks a considerable advance on the older theories and has thrown considerable light on the distribution and movement of water in actual soil. A discussion of this theory is outside the

scope of the present book and the student may be referred to the discussions of W. B. Haines¹ and R. A. Fisher².

In natural soils, the water relationships are dominated by the presence of colloidal material. The moisture associated with soil colloidal material has been termed "*imbibitional moisture*" or "*water of imbibition*." The imbibitional moisture has been considered to consist of *gel water* associated with the colloidal material itself and "*vesicular water*" held in the interstices of the gel structure. The work of Hofmann, Endell, and Wilm (p. 133) has shown that water is actually stored between the cleavage planes of the clay mineral montmorillonite, which can alter their spacing according to the amount of moisture present. S. Mattson³ regards imbibition as essentially an osmotic phenomenon depending on the presence of active exchangeable cations and has propounded a theory of water retention based on the Donnan equilibrium. It is now generally held that "imbibitional moisture" cannot be considered as a definite category.

It is evident that soils differ considerably in their capacity for water retention. Thus, a heavy clay soil with 10% of moisture might be apparently dry, whilst a light sandy soil with the same amount would be visibly moist. Different stages of moistening have been distinguished and the capacity of soils for moisture retention has been compared by the use of defined states of moistening, varying from the moisture retained by air-dry soils to the maximum water-holding capacity of a soil in immediate contact with a free water surface. In the ensuing sections we shall discuss some of the measures proposed for characterizing the capacity of soils to retain moisture.

It should be remarked at the outset that there is some choice of methods of expressing the water content of a soil. If the weight basis be chosen, the result may be expressed either on the moist soil or on the dry soil. For most purposes, the latter mode of expression is preferable, since it gives a truer picture of the amount of water associated with a

unit weight of soil. For some purposes, it is convenient to express results as a volume percentage. This method is appropriate when results are to be considered in connexion with pore-space. Here the results may be calculated to the volume of the total soil or to the volume of the actual soil particles. The relationship of these modes of expressing water content may be seen from the following example (Table XX) for a hypothetical soil having apparent density 1.25, true density 2.50, and pore space 50%.

TABLE XX. — CORRESPONDING PERCENTAGES OF WATER BY WEIGHT AND VOLUME FOR A TYPICAL SOIL

Percentage moisture by weight		Percentage moisture by volume	
Moist soil	Dry soil	Total soil	Actual soil
28.6	40	50	100
24.4	32	40	80
19.4	24	30	60
13.8	16	20	40
7.4	8	10	20

HYGROSCOPIC MOISTURE

When a sample of soil, dried in an ordinary atmosphere, is placed in an oven at 100-105°C., or in a completely dry atmosphere, a small amount of water is driven off. This is called *hygroscopic moisture*, and is believed to be present in the form of thin films of approximately molecular thickness. The percentage of hygroscopic moisture in a given soil varies with the state of saturation of the atmosphere with respect to water vapour. In equilibrium with a perfectly dry atmosphere, the hygroscopic moisture is completely lost, but as the degree of saturation or relative humidity of the atmosphere with which the soil is in equilibrium increases, the moisture content of the soil also increases. This relationship has been investigated by M. D. Thomas⁴ and by A. N. Puri, E. M. Crowther, and B. A. Keen⁵. The curves

obtained are of a general sigmoid type with a point of inflexion corresponding with 50% humidity. Many of the earlier investigators attempted to determine the moisture content of the soil in equilibrium with a saturated atmosphere, believing that the figures thus obtained represented the hygroscopic capacity, i.e., the maximum amount of moisture that the soil could retain by hygroscopicity. The work of the above-mentioned authors shows that this conception is erroneous. Even if the experimental difficulties of maintaining an atmosphere in a state of saturation at a constant temperature were surmounted, the soil exposed to such an atmosphere would continue to take up moisture until it (the soil) became completely saturated. The curves connecting moisture content with relative humidity are in fact composite in character, and the point of inflexion may represent approximately the change from the curve indicating hygroscopic to that indicating capillary condensation.

H. A. Wadsworth⁶, in a discussion of the curves connecting moisture content with surface force, considers that the sorption in the lower part of the moisture relative humidity curve may be considered as relating to water held by "chemisorption," i.e., by surface adsorption, by hydration of ions on active surfaces, by sorption on crystal surfaces of minerals, including planar water, and also a certain proportion of the moisture held by organic matter. In the upper part of the curve moisture is considered to be held in the fine pores of the soil material and increases rapidly as relative humidity increases.

The degree of saturation of a closed atmosphere can be controlled by using equilibrium solutions, generally sulphuric acid, of varying strength. Thus, in the Bureau of Soils, Washington, 99.0% saturation is obtained by using 2% (by vol.) sulphuric acid. Puri, Crowther, and Keen propose 50% saturation, attained in equilibrium with sulphuric acid of density 1.3321. It is shown that the value obtained in equilibrium with a 50% saturated atmosphere does not differ greatly from the moisture content of ordinary

air-dry soil, since there is a fairly wide range on either side of this point over which the hygroscopic moisture content does not vary greatly. The significance of hygroscopicity determinations has been discussed by A. N. Puri⁷.

The hygroscopic moisture content as ordinarily determined on air-dry samples, although it gives an approximate relative measure of a soil's hygroscopicity, is influenced by changes in atmospheric humidity. The same sample of soil may give different values on different days if there is any marked change in atmospheric conditions. Yet, on considering a large number of results, it is evident that the highest figures are given by soils rich in clay or organic matter and by soils rich in sesquioxides, such as laterites.

B. A. Keen and J. R. H. Coutts⁹ examined the correlation of the moisture content of soils in equilibrium with an atmosphere of 50% humidity with other soil constants. Whilst a high correlation was found between hygroscopicity and clay content, the correlation between hygroscopicity and ignition loss was less close. Since ignition loss is, except in heavy clay soils, mainly due to organic matter, this result might appear to imply that organic matter makes a small contribution to the hygroscopic capacity of the soil. Against this may be set the high values actually obtained for the hygroscopic moisture of peat soils. In some further studies on Natal soils, J. R. H. Coutts¹⁰ found a much higher correlation between moisture content at 50% humidity and ignition loss, but this was not surprising in view of the clay character of the soils used, for the loss on ignition in such cases is mainly due to water of constitution. Further work is desirable to establish the correlation which undoubtedly exists between hygroscopicity and organic matter content. The data obtained hitherto do not permit the accurate expression of hygroscopicity as a function of clay and organic matter content, but merely indicate correlations.

In a soil low in colloidal material, hygroscopic moisture is retained as films of approximately molecular thickness on the surface of the mineral particles, and the amount present

under standard conditions is a measure of the total surface. In ordinary soils, however, there is a certain amount of colloidal material and this is principally responsible for hygroscopic moisture retention.

E. A. Mitscherlich¹¹, who has used hygroscopicity as a measure of the specific surface, has attempted to distinguish between the total surface, which is concerned with the absorption of hygroscopic water, and is mainly a property of colloidal material, and the exterior surface of the mineral grains and soil crumbs. He has sought to obtain a measure for exterior surface by determining the amount of absorption from an atmosphere containing an organic vapour such as benzene, it being assumed that the benzene does not enter the interior micellar structures of the colloid material. R. K. Schofield³ considers, however, that the difference in the behaviour of the soil to water and to liquids such as benzene is one of degree rather than of kind. The theoretical basis of Mitscherlich's method and of other methods depending on similar comparisons is thus open to question.

An air-dry soil is incapable of yielding water to plants or of permitting microbiological activity. Further, although certain changes have been observed after long storage of air-dry soils, the rate of chemical change is inappreciable compared with the rate in moist soils, i.e., soils which contain moisture in excess of that retained by hygroscopicity.

MOISTURE CAPACITY

From the standpoint both of soil genesis and also of plant nutrition, the investigator is principally interested in moist soils. It is only in such soils that the pedogenic processes and the complex changes, involving the microbiological population and surface vegetation, take place.

It is a matter of common observation that even under similar climatic conditions, soils vary greatly in their water relationships. Generally speaking, sandy soils are dry and readily allow the rainfall to drain away from them, whilst clay soils are wet and retentive of the moisture obtained

from the rainfall. It is important to understand the mechanism of water retention, and also to possess methods of comparing this property in different soils.

A measure of the water-holding capacity of soils once widely used is the so-called *maximum moisture capacity*, obtained by determining the amount of water which a given quantity of soil can retain when placed in a shallow cylindrical vessel with a perforated bottom, saturated with water, and allowed to drain freely. The figure obtained represents the amount of water which a soil can retain in equilibrium with and in the vicinity of a free water surface. Various modifications of Hilgard's original method have been proposed, for example, that of B. A. Keen and H. Raczkowski¹³, but it should be noted that the results obtained correspond closely with the pore-space, for under such conditions on the larger voids will be empty of water. Further, the determinations are made on soil that is not in its field structure.

MOISTURE EQUIVALENT

When a soil is saturated up to its maximum water-holding capacity a large proportion of the water is only loosely held in the capillary spaces. In the determination of *moisture equivalent*, soil is placed in cups with perforated bottoms and submitted to a centrifugal force equivalent to 1000-2000 times that of gravity. The water held in the coarser interstices is thus removed and the only moisture retained is that in the smaller interstices associated with the soil colloids.

G. J. Bouyoucos¹⁴ has proposed a simplified method for determining moisture equivalent by submitting wet soil to suction on a Buchner funnel and determining the moisture content after water has ceased to drain away. Precautions are necessary to avoid errors by evaporation.

A. F. Lebedev¹⁵ has shown that the value obtained for the moisture equivalent varies with the centrifugal force used and proposes the use of 18,000 g., at which a limiting value,

which he terms the *maximum molecular water capacity*, is reached. It may be doubted whether the figure thus obtained represents a limiting value. Theoretically there should be a continuous decrease in moisture content with increase in the centrifugal force applied.

“ STICKY POINT ”

F. Hardy¹⁶ has proposed, as a measure of the water capacity of soils, the moisture content of a soil-water paste which can just be worked in the hands without being adhesive—the so-called *sticky point*. This is considered to represent the point at which the maximum imbibitional capacity of the soil colloidal material is satisfied. But since a sticky point can be obtained for fine sands and for kaolin, in which colloidal gel material is present in very small amounts, the moisture present at this limit must include some interstitial water.

B. A. Keen and J. R. H. Coutts⁹ have determined the sticky point of a number of soils from which most of the colloidal organic matter had been removed by treatment with hydrogen peroxide. The relationship with the clay content is approximately linear. Plotting the “ sticky point ” moisture, S_p , against the clay, the curve cuts the S_p axis at about 16% moisture. From this it may be deduced that a soil with no colloidal material should show a sticky point of approximately 16% moisture by weight. For an “ ideal soil ” with close packing the moisture content calculated on a weight basis with the interstices filled would be 14.6%

B. de C. Marchand¹⁶ finds, for Cape Western Province soils, that the sticky point water, expressed as a volume percentage, is given by the equation

$$S_v = 0.58 \text{ Clay} + 26 \pm 1.2$$

The value 26 in this equation is in complete agreement with the theoretical pore-space for an ideal soil—a result which can only be possible by reason of compensating adjustments, since the actual particles of soils are neither spherical nor of uniform size.

J. A. Prescott and H. G. Poole¹⁸, working with Australian soils, found a tendency for the sticky point moisture to have a minimum value at 10% of clay.

The contribution of organic matter to the "sticky point" water capacity of soils has not yet been determined, but it is known that highly organic soils show high "sticky points."

It should be added that the moisture conditions in a soil at the "sticky point," as determined in the laboratory, are rarely, if ever, attained under natural conditions. In this determination, the moistened soil is brought into the single-grain or puddled condition and the paste consists simply of soil with water completely saturating the colloidal gels and filling the interstices.

IMBIBITIONAL MOISTURE

A. F. Joseph¹⁹ attempted to determine the imbibitional moisture in the clay fractions of a series of soils by obtaining for each soil the moisture equivalent and the xylene equivalent. Assuming that, in the case of xylene, there is no imbibition by gels, then the difference between the two values should give the imbibitional moisture, i.e., the moisture associated with the colloidal gel material.

Some results obtained by this method are given in Table XXIII.

TABLE XXIII.—MOISTURE EQUIVALENT, XYLENE EQUIVALENT, AND IMBIBITIONAL MOISTURE OF CLAY FRACTIONS WITH DIFFERENT CATIONS (JOSEPH)

	Original Clay	Sodium Clay	Calcium Clay
Moisture equivalent by weight ...	68.7	125.0	63.0
Xylene equivalent by weight ...	11.7	11.4	11.1
Imbibitional moisture by volume	143.0	292.0	131.0

Some interesting points arise from these data. In the first place, it will be noticed that the xylene equivalent is

practically the same for the original clay, the sodium clay, and the calcium clay. The imbibitional moisture is, however, far higher in the sodium clay than in the other clays. This is in agreement with the highly dispersed character of sodium soils. The original soil, containing principally calcium as its exchangeable base, does not markedly differ from the calcium soil. The clay fractions of alkaline soils would probably approximate to sodium clays.

In Table XXIV are given a selection from Joseph's data for the imbibitional moisture of some representative clays. The correlation of the figures obtained for imbibitional moisture with the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio may be noted. It should be added that the clay of china clay differs from the clay of ordinary soils. Soils having a clay $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio of 2.0 would retain appreciable amounts of imbibitional moisture.

TABLE XXIV.—IMBIBITIONAL MOISTURE AND SILICA-ALUMINA RATIO FOR CLAY FRACTIONS (JOSEPH)

			$\text{SiO}_2/\text{Al}_2\text{O}_3$	Imbibitional moisture Volume %
China clay	...	...	2.11	5.0
Ball clay	...	...	2.66	39.5
Subsoil clay, N. Wales	...	...	2.84	101.6
Kassala alluvium	...	...	3.77	79.2
Badob	...	...	3.90	100.8
Blue Nile alluvium	...	...	4.53	128.0
Bentonite	...	...	6.96	261.0

CATEGORIES OF SOIL MOISTURE

From the foregoing account it may be seen that a considerable body of investigation has been directed towards the classification of soil moisture into definite categories. Thus, L. J. Briggs²⁰ in 1897 proposed that soil moisture should be divided into three categories, namely, (1) hygro-

scopic moisture; (2) capillary water, i.e., water held by surface tension in films and in capillary spaces; and (3) gravitational water, i.e., water free to move downwards under the influence of gravity. Briggs and his co-workers developed this classification further with special attention to the capillary water, which was further subdivided according to its availability to plants. The idea of the *lento-capillary point*, the point at which the movement of soil moisture becomes so slow as to be ineffective was introduced.

G. J. Bouyoucos²¹ proposed a classification based on the idea of "unfree water," i.e., water held so closely by the soil colloids that it is not readily available to plants and freezes only at temperatures considerably below 0°C. This classification is briefly as follows:—

Gravitational water.

Free water, freezing at not less than $-1.4^{\circ}\text{C}.$ and available to plants.

Unfree water.

a. Capillary—freezes at $-4^{\circ}\text{C}.$, strongly held and slightly available to plants.

b. Combined—does not freeze at $-78^{\circ}\text{C}.$, and is non-available to plants.

Bonyoucos's classification has been strongly criticized but served a useful purpose in directing attention to the great force with which the water of fine capillaries is held by the soil.

A. F. Lebedev²² proposed the recognition of the following forms of soil moisture:—

Water vapour.

Hygroscopic water.

Film water.

Gravitational water.

This and similar classifications of soil moisture are all based on the capillary tube approach to the problem of soil moisture. It is now generally held that such classifications are arbitrary, and do not correspond with any real classification of soil moisture. We have already seen how

the concept of a definite hygroscopic capacity proved illusory. Similarly with such categories as imbibitional moisture, capillary water, and gravitational water, their definition can be made only in terms of conventional methods of determination. The modern tendency is to seek for the expression of the moisture status of soils in the form of continuous functions.

CAPILLARY POTENTIAL AND pF VALUE

The various measures proposed and used for characterizing water-holding capacity of soils all measure the wetness of soils under certain specified conditions. E. Buckingham²³ first attempted to give this idea precision by introducing the term *capillary potential* on the analogy of temperature and electrical potential. Just as temperature differences determine the flow of heat, and electrical potential the flow of electricity, so capillary potential may be supposed to determine the translocation of moisture in soils. Thus, if at two adjacent points in the soil there is a difference of capillary potential, moisture movement should result. Buckingham's capillary potential was expressed in terms of the equivalent water column corresponding with the suction pressure or pressure-deficiency required to cause water movement from the soil, or the positive pressure for water movement into the soil at a given moisture content. Capillary potential is a measure of the difference in free energy between water in bulk and soil water under the given condition. It may be defined as the work required to move a unit mass of water against capillarity from the level of a free water surface, i.e., the water-table, to a given point above this level.

It is necessary to point out that inasmuch as capillary potential increases with decreasing moisture content, water movements will tend to take place from points of low to points of high capillary potential. Capillary potential is thus an inverse measure of wetness and the analogy with temperature and electrical potential is actually reverse. It is important to bear this in mind in the following discussion.

Capillary potential is conveniently expressed as suction pressure in centimetres of water. The relationship between suction pressure and moisture content in the range, corresponding with suction pressures up to about 100 cm. of water can be easily studied by means of a simple apparatus due to W. B. Haines²⁴. The soil is placed in a layer of about 2 cm. on a Buchner funnel, the bottom of which is covered by a sealed-on filter paper. The funnel is connected

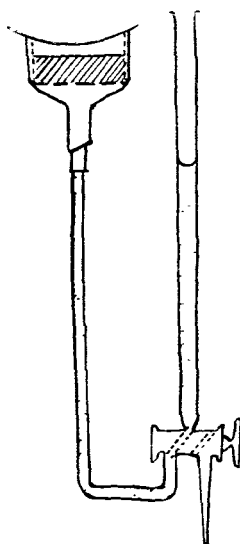


FIG. 14.—Apparatus for studying suction pressure.

with a burette-manometer as shown in *Fig. 14*. The apparatus is filled with water and, by varying the height of the burette, varying pressure deficiencies, indicated by the difference between the height of the water in the burette and the mean height of the soil layer, can be obtained. The burette reading serves to indicate withdrawal of water from the soil as suction pressure is increased. At first very little water is withdrawn from the soil, corresponding with the stage when concave menisci are formed at the surface of the

soil. In the next stage there is a considerable withdrawal of water corresponding with the evacuation of the larger voids. As successively smaller voids become empty, the rate of removal of water with increasing suction pressure slows down. The form of the curve connecting suction pressure with moisture content is characteristic and differs for different soils. If instead of plotting moisture content against suction pressure, the percentage void space is plotted, a curve is obtained giving the distribution of pore-spaces of different sizes.

In Haines's method and others of the same type the suction pressure is given by the difference in height between the layer of soil and the level of the free surface in the other limb of a U tube. The situation is essentially similar in the case of a column of soil above a water table and in a state of equilibrium. Over the lower part of the range, the suction pressure increases proportionally with the height above the water-table and the moisture content falls off in correspondence. This, however, is true only over the range within which soil moisture movements are sufficiently rapid for equilibrium to be attained within the period of the experiment. At high suction pressures, i.e., above about 1,000 cms., movements are so slow that there is little change in moisture content with increasing height. The equilibrium is only apparent and, given sufficient time, adjustment would eventually take place.

R. K. Schofield²⁵ has proposed the logarithm of Buckingham's capillary potential as a measure of the moisture status of the soil and for this he proposes the term pF. It has the advantage of analogy with pH and enables the enormous differences in capillary potential between dry and moist soil to be compressed within a convenient range.

An example of the translation of a moisture constant into terms of pF may be quoted from Schofield. In modification of a method proposed by G. J. Bouyoucos¹⁴, he measures the amount of water retained after submitting wet soil to suction on a Buchner funnel so packed as to allow free passage of

water but not of air. Any desired pressure difference up to one atmosphere can be maintained across the filter. A suction pressure corresponding with one atmosphere is

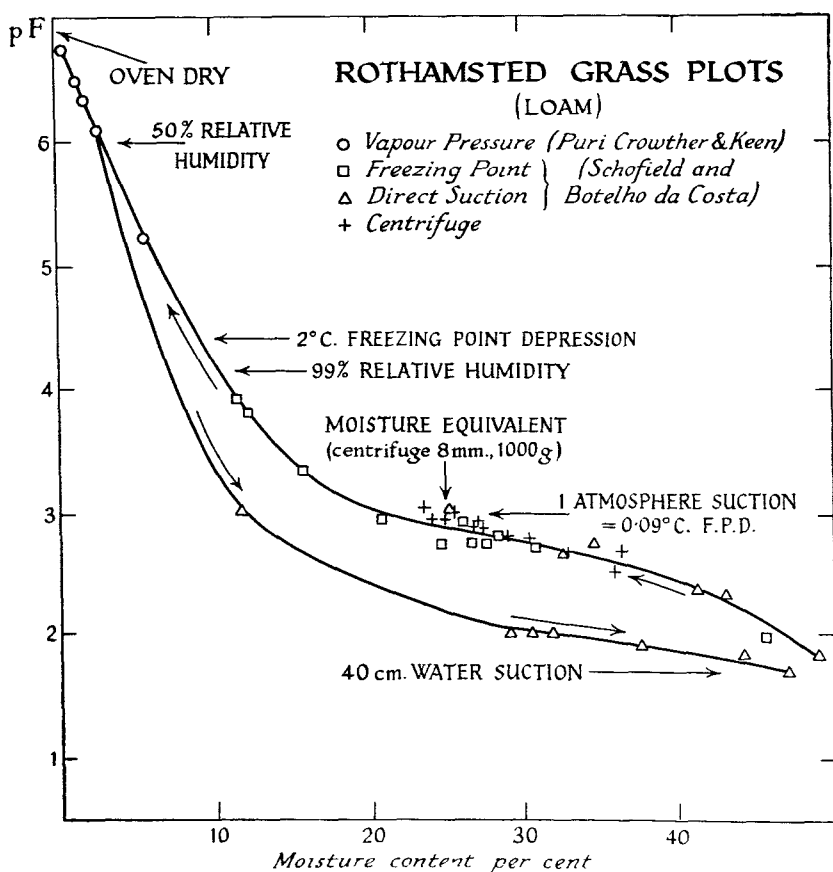


FIG. 15.—Moisture-pF curve of Rothamsted soil. (SCHOFIELD.)

equivalent to that of a column of water about 1,000 cm. in height. The soil in equilibrium is said to have a pF of 3 ($\log_{10} 1,000$) and it is a simple matter, by making corresponding direct determinations of moisture content, to obtain a number of points connecting moisture content with pF values

up to 3. To obtain higher pF values it would be necessary to use pressure above the filter. In the above experiment the starting point is from wet soil. By a variation in the method

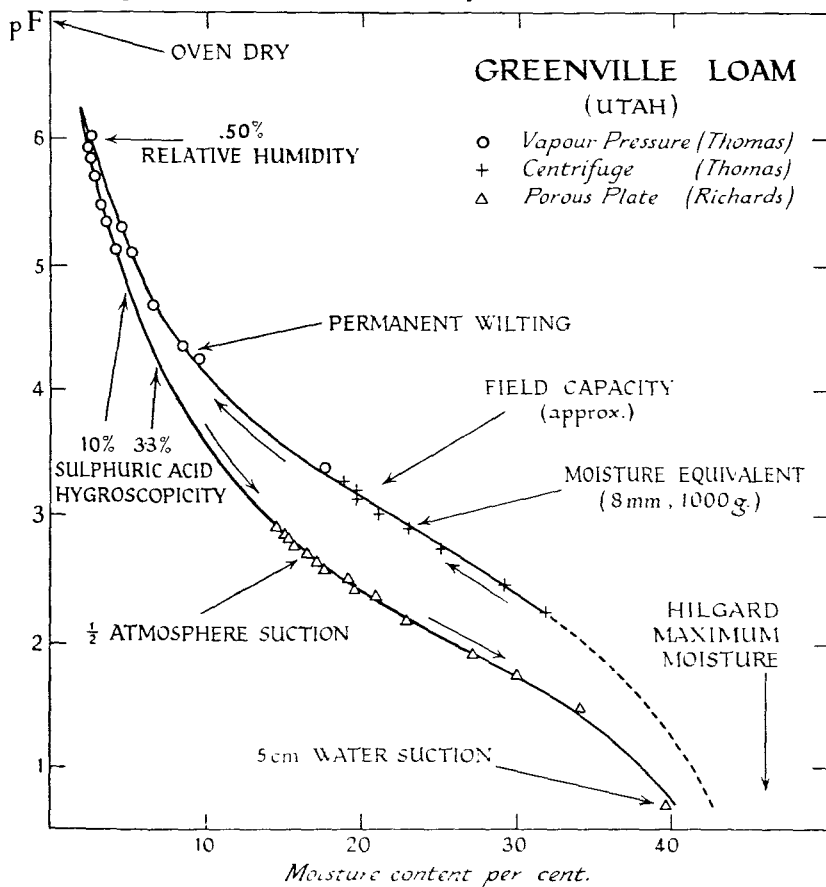


FIG. 16.—Moisture-pF curve of Utah soil. (SCHOFIELD.)

of experiment it is possible to determine the amount of moisture which the soil will absorb against a given pressure difference. It is found that different pF values are obtained for the moisture content at the same pF according to whether the soil is being dried out by suction or being wetted by

absorption against pressure. There are thus two curves connecting pF with moisture content, one for drying and the other for wetting. This is in harmony with the observed result that moisture movement does not necessarily result when there is a moisture gradient, or rather that movement may be so slow as to be unobservable within the period of an ordinary experiment. Schofield has used other data to obtain points on the pF -moisture content curve. Thus the depression of freezing point and the aqueous vapour pressure of soils can, by appropriate equations, be translated into terms of pF . These, together with values obtained by suction methods and by centrifugal methods, can be combined to give curves for wetting and drying. Such a curve is shown in *Fig. 15*, which relates to a Rothamsted soil, the upper curve indicating drying conditions and the lower wetting conditions. A similar curve deduced from published results is given in *Fig. 16*.

The discrepancy between the wetting and drying curves, usually referred to, but not explained, as an hysteresis effect, is to some extent due to the fact that the determinations were made on laboratory samples and not under field conditions. The drying curves were obtained with samples first air-dried and then flooded with water. The pore-space here is much greater than under field conditions. A. L. C. Davidson and R. K. Schofield²⁶, in an investigation of suction pressures with porous stones, found that equilibrium was more rapidly obtained under drying than under moistening conditions. The slow wetting of air-dry samples, however, gives conditions more closely approximating to those in the field.

The distribution of water in the soil by capillary transmission has been examined and formulated by E. C. Childs and H. H. Nicholson²⁷.

The conception of capillary potential translated into terms of pF , together with the recognition that for every soil there are two pF -moisture content curves, one for wetting and the other for drying, constitute an important clarification of our ideas on soil moisture problems. It is now

possible to have a convenient comparison of the moisture status of soils by means of pF values.

The implications of the pF conception have not been fully worked out, but one example may indicate its use. In the supply of water to a plant, transfer from soil to plant roots may be considered to result from a difference in capillary potential or pF . As the moisture content of the soil falls the capillary potential and pF increase. A point is eventually reached when the soil is no longer able to supply water rapidly enough to cover losses by transpiration and, with loss of turgor, the plant wilts. The point at which this occurs is termed the *wilting point*. Schofield has shown, from a consideration of the data for moisture contents at the point of permanent wilting of plants, that this point may be represented by a pF of about 4.2 for a number of soils. Other critical moisture conditions can be similarly defined in terms of pF .

WATER MOVEMENTS IN SOILS

The earlier work on water movements in soils was dominated by the capillary tube hypothesis. Thus, W. H. Green and G. A. Ampt²⁸ developed equations for the flow of water through soils based on Poiseuille's equation for the flow of liquids through capillary tubes, obtaining equations for downward percolation, upward motion, and horizontal motion. Experimental data with coarse materials were found to agree fairly well with the equations obtained, but complications were introduced by the erroneous assumption of complete saturation behind a moving water front, whilst still more serious difficulties were introduced in actual soils by the swelling of colloidal material on wetting. The same objections may be applied to the use of the ideal soil hypothesis to obtain equations for the movement of water in actual soils.

Probably the most fruitful conception in the study of water movements is that of capillary potential, or its more convenient form pF , introduced by Schofield. According to

this, water tends to move from a point of low to a point of high capillary potential. As has been seen, for each moisture content there are two pF values, one for wetting and the other for drying conditions. Thus a dry soil placed in contact with a wet soil will abstract water from it until its wetting pF is equal to the drying pF of the moister soil. A soil can thus be in capillary equilibrium with a soil of higher moisture content from which it is abstracting moisture.

It is important to realize that when water is added to a column of dry soil it will not diffuse throughout until a uniform moisture content is attained, but will only moisten a limited depth of soil. Beyond this limit there is a sharp decrease in moisture content. This was recognized by J. A. Widtsoe and W. W. McLaughlin²⁹ in their proposed *lento-capillary point*, at which capillary movements become sluggish and ineffective.

Schofield pictures the absorption of water applied to a dry soil as involving two stages. In the first stage water runs rapidly through the larger interstices and is rapidly absorbed by the soil, which is moistened to a degree corresponding with a very low pF , and to a depth corresponding with the amount of water available. There is now a diffusion involving transfer from the wet upper layer to the dry lower layer. Movement into this layer where wetting conditions will obtain is against suction by the upper layer with drying conditions. After a time movement ceases, the limit being set by the pF value above which the rate of wetting of the dry soil is negligible.

VARIATIONS IN MOISTURE STATUS IN THE SOIL PROFILE

The capacity of a soil to retain water cannot be defined without reference to the soil horizons which lie below it. Just as, from the standpoint of soil genesis, the unit of study is the soil profile, so in studies of soil moisture, the system to be considered is the whole succession of horizons down to the ground-water level, or if this is very deep, down

to the limit of atmospheric influences. And, therefore, although laboratory studies on soil moisture problems are indispensable for the elucidation of the fundamental principles, the final synthesis can be made only face to face with actual soil profiles.

If a hole or trench be dug in the soil in a valley bottom, a level is reached at which there is complete saturation. If the hole is sunk still further, water will stand in it up to this level, which is called the *water-table*. The water-table usually follows the contours of the land in a less accentuated manner. The depth below the surface at which it is encountered increases as the sides of a valley or hill are ascended. In the bottoms of valleys it approaches the surface of rivers and lakes. Complications are produced by impervious strata, so that in some cases the water-table may be quite near the surface in elevated situations. This is sometimes called a "perched" water-table.

Owing to the predominance of rainfall over evaporation during the winter months, and of evaporation over rainfall during the summer months, the position of the water-table fluctuates, generally reaching a maximum at the end of the winter and a minimum at the end of the summer. Abnormal rainfalls or droughts may disturb this general succession.

In many soils, even in humid climates, the water-table lies so far below the surface as to have practically no effect on moisture conditions at the surface. Thus, in the chalk upland soils of England, the water-table is scarcely a factor in the soil moisture problem. It is difficult to assign a limit below which the water-table does not affect conditions in the surface soil. It would be fairly safe to assume that, where this level is more than twenty feet below the surface, the moisture relationships are mainly controlled by the conditions within the layer of free percolation. On the other hand, a water-table lying within four feet of the surface has a definite effect on the moisture relationships at the surface. For example, a certain coarse sandy soil in Anglesey is in agricultural use in low-lying situations where the water-table

is within three feet of the surface, whilst in slightly elevated situations it is blowing dune.

The influence of position relative to a water-table on water content is illustrated by data obtained by E. W. Hilgard⁴⁰ in a sandy alluvium in California (Table XXII).

TABLE XXII.—VARIATION IN MOISTURE CONTENT IN A SANDY ALLUVIUM AT DIFFERENT DISTANCES FROM THE WATER-TABLE (HILGARD)

(From "Soils," by permission of The Macmillan Co., Publishers.)

Inches above									
water-table	1	6	12	18	24	30	36	42	47
Moisture % ...	36.6	35.0	32.5	27.6	21.4	15.3	12.0	10.3	4.3

The moisture content immediately above the water-table will, of course, correspond closely with complete saturation of the pore-space, as in the determination of maximum water-holding capacity, and the gradual decrease in moisture content towards the surface represents the changing equilibrium between gravity and capillary forces. The low moisture content at the surface may be attributed to loss by evaporation.

If we assume that the moisture content at each level represents equilibrium, any moisture in excess of this at any level is subject to gravity and tends to sink to the water-table. Some writers have drawn a distinction between *capillary water* and *gravitational water*, the latter being any water in excess of that which a soil can hold by capillary action at a particular level above the water-table.

We must now examine the distribution of soil moisture in a soil profile from the standpoint of what has been said above on the relationship between suction pressure and soil moisture. Let us consider a column of soil extending from the surface down to the level of the water-table. In ordinary moist soils with irregular space distribution, the moisture present forms a continuous system. Thus, except for a possible dry zone at the surface, all the moisture in the profile

is in capillary connexion. At the level of the water-table the pressure within the soil moisture is approximately that which would obtain at a corresponding free water surface. Above the water-table, however, the pressure falls off with height. Thus, at 1 cm. above the water-table there is a negative pressure or suction pressure equivalent to 1 cm. of water. For some distance above the water-table the suction pressure increases proportionally to the height, but this relationship holds for only a limited distance. The zone over which suction pressure is in linear relationship with height above water-table has been termed the "capillary fringe." But here, as in other aspects of the problem of soil moisture, no hard and fast line can be drawn. In a perfectly uniform column of soil, the moisture content in the upper part of the profile, if in temporary equilibrium, would tend to correspond with a pF of about 3, the so-called field capacity, even although the water-table were more than 1,000 cm. below the surface. Near the water-table, or at the surface, where the water-table is at small depths, the equilibrium moisture content approximates more closely to the pF corresponding with the height above the level of complete saturation.

DISTRIBUTION OF ADDED WATER IN THE SOIL PROFILE

In very wet soils, a considerable proportion of the moisture present is free to move downwards under the influence of gravity and, eventually, an equilibrium distribution is attained depending on the position of the water-table and the moisture capacity of the different horizons.

The distribution of moisture applied to the surface of a dry soil is shown by some experiments by C. F. Shaw³¹. Using 36 inches of dry soil and applying a 6-inch head of water, it was found that after 24 days the moisture content was fairly constant at about 20% down to 19 inches and then fell off to 3.33% at about 30 inches. After 123 days the moisture content decreased slightly from 17.32% at the surface to 16.16% at 24 inches. It was concluded that this represented practically the equilibrium distribution of the

water applied, apart from possible movements in the vapour phase. The average value, 16.79%, termed by Shaw the *normal moisture capacity*, approximates fairly closely to

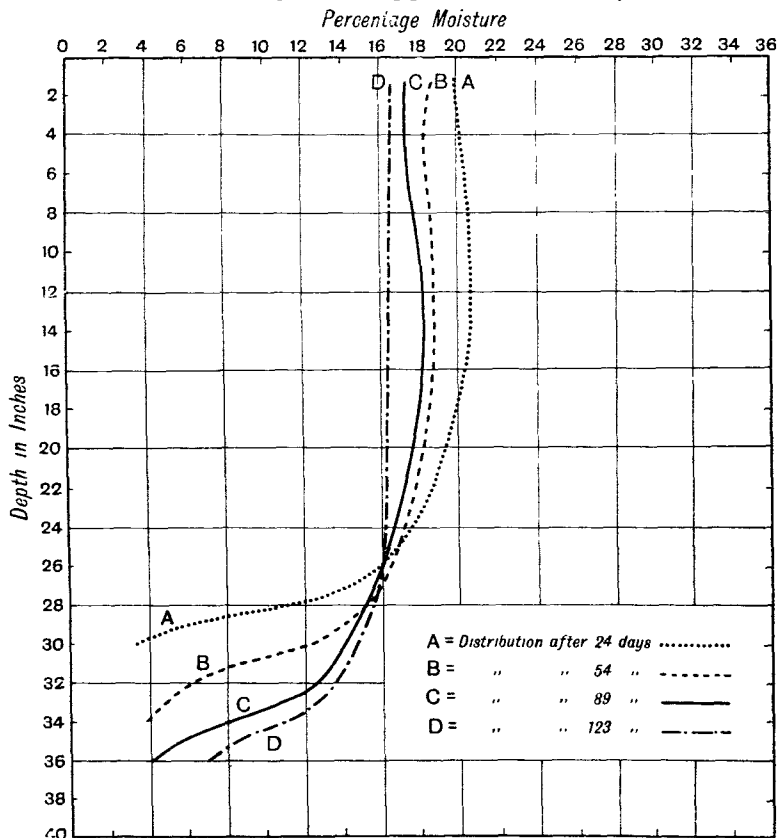


FIG. 17.—Distribution of water in tubes receiving a 6-inch irrigation, after prolonged periods of adjustment. (C. F. SHAW.)
From "Soil Science"—(by permission.)

the moisture equivalent for the same soil, namely, 15.88%. These results are shown graphically in *Fig. 17*. It is suggested that, for moisture contents up to the normal moisture capacity, capillary movement is negligible. The normal moisture capacity of Shaw is thus apparently the lento-

capillary point of Widtsoe and McLaughlin, but appears to lie above rather than below the moisture equivalent. The subsequent drying out of the soil would take place entirely by evaporation, which would not necessarily be entirely at the surface, but might involve vapour movements from lower levels. In this connexion, the influx and efflux of air consequent on diurnal temperature variations is probably of importance.

Shaw's results were obtained with a uniform soil under laboratory conditions. In a natural profile, the variations in the nature and content of colloidal material throughout the profile would result in a different distribution of moisture. Presumably the presence of a considerable proportion of organic matter in the surface soil would be reflected in a higher equilibrium moisture content. The march of the curve down to the limit of wetting would, indeed, tend to follow that of the moisture equivalent.

F. J. Veihmeyer and A. H. Hendrickson³² have studied the *field capacity* of certain irrigated soils in California. By field capacity is understood the "amount of water held in the soil after excess gravitational water has drained away and the rate of downward movement has materially decreased." For all except the lightest soils, field capacity approximates closely to the moisture equivalent as determined by the modification of the method of L. J. Briggs and H. L. Shantz. It corresponds, according to Schofield, with a pF of about 3. In the absence of evaporation, from two to three days after irrigation are required for the field capacity to be reached, but conditions are materially altered by the presence of impervious layers. If an amount of water is applied either as rain or by irrigation to a dry soil less than that to restore it to field capacity throughout, when equilibrium is reached, there is a fairly sharp transition from moistened to unmoistened soil, all the moist soil showing approximately the same degree of wetness relative to the moisture equivalent. This is readily intelligible when it is realized that capillary transmission becomes negligible below a certain moisture content, which may be, for practical purposes,

equated with Widtsoe and McLaughlin's werto-capillary point (p. 284).

In the presence of a water-table near the surface, the equilibrium moisture distribution is modified. In the Shaw experiment, a water-table at, say, 24 inches below the surface would be reflected in an increased moisture content, as in the Hilgard experiment mentioned on page 286. The presence of impervious or relatively impervious strata would have the same effect as a water-table.

CAPILLARY RISE

In the earlier literature on soil moisture, dominated by the capillary tube hypothesis, considerable importance was attached to the lift of water by capillary action from a water-table or a moist subsoil. It is now known that whilst such movements may take place to a limited extent in wet soils, in other words with soils at low pF values, a limit is soon set to the amount of rise which can thus take place.

Thus C. F. Shaw and A. Smith³³, in an experiment with columns of Yolo loam of varying height above an artificially maintained water-table, found that with 4 foot tubes the average monthly loss was 3.595 cm., with 6 foot tubes 1.92 cm., with 8 foot tubes 1.0 cm.; and with 10 foot tubes only 0.165 cm. Thus with a water-table at 10 feet below, the capillary rise, which presumably controlled the amount of evaporation, was negligible. Similarly, B. A. Keen³⁴ found that with 6 foot cylinders of soil sunk in the ground and originally saturated with water, the water-table in a heavy loam did not fall below 80 cm. In fine sand the limit was 70 cm., and in coarse sand 35 cm. from the surface. He concluded that capillary rise was ineffective over the depths indicated. An examination of the data in both of the above series in the light of the pF hypothesis would be of interest.

LOSSES OF MOISTURE BY EVAPORATION

Under a covering of natural vegetation, losses from the soil to the atmosphere are principally by transpiration from the leaves of plants. Under crops, the losses are partly by

evaporation from bare soil. The rate of loss by transpiration and evaporation depends partly on meteorological factors such as temperature, humidity, and wind velocity, and partly on the character of the transpiring vegetation or evaporating soil. Other things being equal, moisture losses are greater under a covering of vegetation than with bare soil. The diminution in evaporation consequent on deforestation may lead to waterlogging. (See p. 362.)

The principal circumstance affecting the evaporation of moisture from soils is the temperature. This is illustrated by the data, reported by A. D. Hall³⁵, obtained from the Rothamsted lysimeters. The amount of percolation is measured from columns of soil in which the original structure has been preserved unaltered. The surface of the soil is maintained tilled but uncropped. The rainfall is completely accounted for by evaporation and percolation since there is no run-off from the surface. Hence, by measuring the percolation, the amount of evaporation can be determined. The data are shown in Table XXV.

TABLE XXV.—TEMPERATURE, RAINFALL, PERCOLATION, AND EVAPORATION AT ROTHAMSTED (HALL)

Month	Rainfall Average	Temperature 26 years average deg Fahr.	Percolation through 60 inch gauge inches	Evaporation inches	Daily Evaporation inches
Jan. ...	2.32	36.6	1.96	0.36	0.0116
Feb. ...	1.97	38.2	1.48	0.49	0.0175
Mar. ...	1.83	40.9	0.95	0.88	0.0284
Apr. ...	1.89	45.5	0.53	1.36	0.0453
May ...	2.11	51.2	0.50	1.61	0.0520
June ...	2.36	57.5	0.62	1.74	0.0580
July ...	2.73	60.7	0.65	2.08	0.0671
Aug.	2.67	59.9	0.58	2.09	0.0674
Sept.	2.52	55.9	0.76	1.76	0.0587
Oct. ...	3.20	48.0	1.68	1.52	0.0490
Nov.	2.86	42.6	2.04	0.82	0.0273
Dec. ...	2.52	37.7	2.04	0.48	0.0156

There apparently is a close correlation between temperature and the daily evaporation. R. J. Koshal³⁶, however, suggests that the high percolation in the winter months represents the accumulation of water during the wet autumn months, whilst the low figures in summer may be due to the delayed effect of the light spring rainfall. It cannot be doubted, however, that there is a considerable increase in the rate of evaporation with temperature. It can be readily understood that, in tropical climates, the rate is still greater. Where losses are due to transpiration from plants, the temperature effect will be similar.

Evaporation is markedly increased by wind, particularly if the atmospheric humidity is low. The rapid drying out of soils in east winds is well known to practical agriculturists.

The effect of variations in atmospheric humidity is shown by some data from Masure, cited by E. Ramann³⁷ (Table XXVI).

TABLE XXVI.—EFFECT OF VARYING HUMIDITY ON RATE OF EVAPORATION FROM SOIL (MASURE)

Temperature °C	Relative Humidity %	Evaporation mm.
17.6	74	0.93
17.7	79	0.62
17.0	89	0.38
17.2	91	0.25

The great differences in the rate of evaporation depending on temperature, humidity, and wind velocity, involve corresponding variations in the amount of percolation through the soil. And therefore the rainfall, in itself, is a very inadequate measure of the leaching to which a soil is subjected. With a mean annual temperature of 5°C, varying between 0° and 10°C, a mean annual rainfall of 20 inches would be sufficient to furnish drainage. The same rainfall, with a mean annual temperature of 25°C, varying between 15°C and 30°C, would be insufficient to outweigh evaporation.

The principal soil factor affecting the rate of evaporation is the moisture content. Generally speaking, in laboratory experiments with thin layers of soil, the rate of evaporation is constant over a wide range of moisture content, but tends to fall off when the region of the hygroscopic co-efficient is approached. Under field conditions, the problem is more

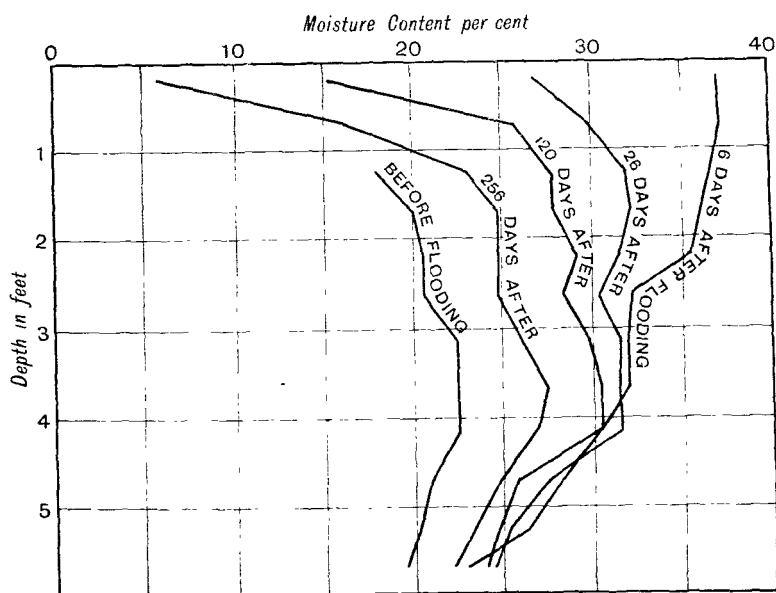


FIG. 18.—Drying out of land after 14 days' flooding. (H. GREENE.)
(From "*Journal of Agricultural Science*"—by permission.)

complex, for the rise of capillary water to the surface plays a part. But when the moisture content at the surface is reduced to the field capacity, further replacement from below becomes slowed down and subsequent losses include evaporation from the body of the soil down to the level at which capillary movement is still possible.

The successive effects of irrigation and evaporation are well shown by some observations of H. Greene³⁸ in the

Sudan Gezira. The soil used was a heavy æolian clay having the following soil moisture constants:—

Moisture equivalent about	... ..	40%
Lento-capillary point about	... ..	28%
Hygroscopic co-efficient about	... ..	14%

It will be noticed that the lento-capillary point for this soil lies considerably below the moisture equivalent.

The results of the investigation are shown diagrammatically in *Fig. 14*. Before irrigation, the moisture content of the soil varied around 20% down to 6 feet. Assuming the absence of capillary movement below the lento-capillary point, this implies that evaporation had taken place not only at the surface, but down to the level explored. The tendency for the curve connecting the moisture content of the unflooded soil to swing to the left at the top reflects the more intense evaporation at the surface.

Six days after flooding, the moisture content was fairly constant over the first two feet and then fell off gradually, the form of the curve suggesting an effect down to at least 6 feet. Subsequently the drying at the surface was rapid, but there was a lag in moisture content at lower levels so that below the first foot, even after 256 days, it was greater than before irrigation. The steadiness of the moisture content below 4 feet during the first period suggests that losses were mainly by evaporation, aided to some extent by capillary rise, from the first four feet. Thereafter, losses occurred throughout the profile.

EFFECT OF DRAINAGE *

It would be of interest to determine, for some typical profiles, the moisture distribution attained after free drainage in the absence of losses by evaporation or gains from rainfall. In this connexion the effect of artificial drainage may also be considered.

*For a discussion on the principles of drainage see J. L. Russell (*J. Agric. Sci.*, 1934, **24**, pp. 544-573).

The soil conditions leading to excessive wetness and calling for improvement by artificial drainage are of three main types:—

(1) The wetness may be due to a regional water-table associated with a pervious soil profile. Such a water-table fluctuates between summer and winter level, and if a system of pipes or ditches is laid out, leading to a suitable outfall, the water-table will be lowered to a level determined approximately by the level of the outfall. The theory of drainage flow has been developed by E. C. Childs³⁹, using the analogy of two-dimensional electrical flow in a sheet conductor.

(2) The wetness may be due to the impervious character of the sub-surface horizons. The effect of this is to give a "perched" water-table which, during the wetter months of the year, may approach the surface. Where there is a natural slope to the local river system the removal of excess water will depend largely on the depth of porous soil above the impervious layer. Thin soils with impervious clay at a few inches below the surface soon become water-logged and, owing to the restriction of root range, are also liable to suffer from summer drought.

The effectiveness of a drainage system in such soils depends on the existence of pervious soil and subsoil immediately above the tiles. If drainage tiles are laid deep in impervious clay, and if the filling becomes consolidated, they cease to function. Similarly with mole drainage, the system is effective only as long as the mole is open to the soil above. Soils with this type of wetness often occur in low-lying situations and therefore in addition to the necessity for securing that the excess water shall reach the tiles or moles it is also necessary to ensure suitable gradients and outfalls.

(3) Local causes of wetness are the occurrence of springs, often where pervious upland soils adjoin lowland soils. Here the unwanted moisture can often be removed by tapping individual springs or by running a ditch or drain along the foot of the slope where the springs occur.

It is important to realize that the removal of water by artificial drainage cannot dry the soil below the moisture content corresponding with the situation of a water-table at the level of the drains. This moisture content will be rather above the field capacity, which would be attained only if the water-table were lowered to a depth considerably greater than that at which drains are usually laid.

The further drying out of wet soils can be effected only by evaporation. It is a matter of common knowledge that, under British conditions, clay soils are persistently wet in winter, even although little rain falls. The reduction of the moisture content of such soils to the point at which they can be worked is mainly dependent on the prevalence of drying winds, and cannot be effected by drainage alone. Similar considerations apply to highly organic soils.

H. H. Nicholson⁴⁰ has shown the importance for drainage of the structure of the surface layer in heavy soils.

LOSSES AND GAINS OF WATER UNDER FIELD CONDITIONS

Movements of liquid water in soils are mainly due to gravitational water. The penetration of water downwards into dry soil depends on the saturation or approximate saturation of superficial layers. After the soil has been dried out to a considerable depth during summer drought, the penetration of moisture is very slow and, under British conditions, the sub-soil sometimes remains fairly dry until mid-winter.

The range of upward capillary movement is now known to be comparatively small. In Keen's experiments, 80 cm. appeared to be the limit of upward movement. From the data of Shaw and Smith, the limit appears to be somewhat greater. Lateral capillary movement of moisture is also confined to small distances. In the absence of water percolating down slopes, soil protected from rainfall remains dry, even if surrounded by soil almost completely saturated with moisture. The soil under cattle sheds in fields is seen to be

quite dry even in mid-winter. A. H. Hendrickson and F. J. Veihmeyer⁴¹ found the maximum lateral movement of moisture from an irrigation trench to be under 30 inches.

Under field conditions, the absorption and disposal of rainfall depends on the texture and structure of the soil. Sandy soils rapidly absorb rainfall and allow ready percolation to the water table. Clay soils oppose a greater resistance to water movements, but differences are observable depending on structure and on the occurrence of compacted horizons. Ferrallitic clays are more open in structure and thus less subject to surface washing under heavy rainfall than aluminosilicic clays, which may not be able to dispose of intense rainfall sufficiently rapidly to prevent run-off and consequent erosion. Other things being equal, the most siliceous clays show the greatest tendency to dispersion, resulting in drainage impedance.

Owing to continued interference through gains from rainfall on the one hand and losses by evaporation on the other, the attainment of moisture equilibrium in a soil profile must be regarded as a purely ideal condition. It is of interest, however, to consider the type of moisture distribution that might be expected in a soil profile with a water-table at such a depth as to be without influence on surface conditions.

During a period when rainfall predominates over evaporation, the tendency will be towards a distribution in which the moisture content at each level will approximate to that represented by the field capacity. This does not necessarily imply an uniform distribution, since the field capacity will vary with the colloidal content and also, to some extent, with the structure. Uniform distribution would be approached only in a uniform soil. Excess of moisture over this ideal distribution, owing to recent precipitation, would be reflected in a higher moisture content at the surface. In the absence of evaporation, this would be translated to lower levels partly by gravitational movement and partly by capillary transmission and would increase the depth of soil

moistened to the field capacity. If the depth thus moistened extends to the zone affected by the water-table, any excess of moisture would be handed on to the ground-water. The rapidity with which such an adjustment is attained will depend on the permeability of the soil to water movements. In heavy soils, adjustments are slow and moisture contents considerably above the equilibrium distribution may persist in the surface horizons for long periods.

With soils of low permeability, heavy rain may result in the saturation of the surface soil. Further precipitation is then disposed of by superficial run-off, with the possibility of erosion of the top soil. The susceptibility of soils to erosion in this way depends on their texture, structure, organic matter content, and the composition of the clay complex. Generally speaking, the tendency to a deflocculated or single-grain structure implies liability to erosion by run-off.

We may now consider the changes in moisture distribution consequent on the cessation of precipitation and the onset of conditions favouring evaporation. If the surface soil is saturated above its equilibrium moisture content by recent rain, losses will take place both by evaporation and also by capillary and gravitational translation to lower levels. Losses by movement to lower levels will cease when the equilibrium moisture distribution has been reached, and thereafter, losses will be entirely by evaporation, at first mainly from the surface, but subsequently, as in Greene's experiments, from the lower horizons. In the earlier stages of drying-out, there is also the possibility of upward capillary movements, but as each successive layer becomes dried to the lento-capillary point, the range of upward movement will be restricted and the losses by evaporation from the superficial horizons will no longer be replaced from below. Since the rate of direct evaporation is greatest at the surface and decreases with depth, the rate of loss of moisture from the soil as a whole must, *ceteris paribus*, decrease when capillary movement to the surface is no longer possible, and will be determined mainly by the direct evaporation from the surface and the subjacent layers.

Where a water-table is present near the surface, conditions will be different, for capillary rise will suffice to replace the losses by evaporation from the surface. But, as we have seen, when the water-table is below a depth of a few feet capillary rise can no longer cover the losses by evaporation from the surface layers. The soil then dries out from the surface downwards.

The drying-out process is much more rapid under a cover of vegetation than with bare soil. E. S. West⁴², in New South Wales, found that with irrigated crops (lucerne, cowpeas, Bokhara clover) the water-table was lowered considerably below that under bare soil, although the crops received 3 to 4 times as much water by irrigation and rainfall. Lucerne is particularly effective in drying out the soil. It is possible that a change in the character of the vegetation, for example, by afforestation or the growth of forage crops, might be effective in aiding the removal of excessive moisture from soils in wet districts.

It has been suggested by A. F. Lebedev³⁴ that, apart from movements of water in the fluid state, a certain amount of vertical translocation takes place in the vapour state. During the winter months, the surface soil is colder than the subsoil, and this may result in an upward distillation conformable with the difference in vapour pressure. Accession of moisture in this way may be a contributory cause of the persistent wetness of soils in late winter when the temperature gradient to the surface is steepest. On the other hand, during the summer months, a downward distillation may take place from the warm surface soil to the colder subsoil, thus reinforcing the losses by evaporation from the surface.

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CHAPTER X

SOILS OF THE PODSOLIC GROUP

INTRODUCTORY

IN this and the ensuing chapters, examples will be given of the soils of the principal world-groups. In arranging the material into chapters, the writer is aware that he is adopting a classification before the general principles underlying soil classification in general have been discussed. The alternative arrangement of discussing the principles of classification and then proceeding to the description of soil groups was considered; but it was felt that such a discussion could be more easily undertaken after the reader had made some acquaintance with the material to be classified. In any case, the titles used as headings for this and the following chapters correspond, in most systems of classification, with the soils assembled under them.

The soils to be described in this chapter occur under humid conditions and are best developed in cold to temperate regions. The podzols* and their congeners are completely leached soils in which calcium carbonate and calcium sulphate are present only as fugitive constituents. The reaction is thus on the acid side of neutrality. The natural vegetation is generally forest or heath, but prairie vegetation is associated with one of the types. The soils of swamp, fen, and marsh vegetation, which appear as local associations

*The alternative spelling *podzol* is generally used in the United States and, I understand, corresponds with the original Russian. After some consideration, I have decided to retain the spelling that has now become familiar to most English readers and is sanctioned by usage.

where drainage conditions are sufficiently impeded, belong to the hydromorphic soils to be discussed in Chapter XII.

PODSOLS

This group of soils, by reason of its wide extent in Russia and Northern Europe, has received more detailed attention than any other group of soils, with the possible exception of the chernozems.

The podsols of the northern hemisphere occupy the humid regions lying to the south of the tundra (p. 352). With their related types, they occupy the greater part of northern and western Europe. They are developed typically under coniferous forest, but occur also under heath vegetation which, in its meagre demands on the plant nutrients of the soil, exhibits a close resemblance to coniferous forest.

A typical podsol profile has already been described in Chapter IV. (p. 84) and consists essentially of three horizons. The A, or eluviated horizon, consists of a layer of peaty material underlain by a more or less bleached layer, relatively poor in humus and sesquioxides. Below the A horizon is the B horizon. This is enriched by certain of the constituents leached from the A horizon. The constituents that distinguish this horizon by their accumulation are humus and sesquioxides. As the conditions of deposition vary with the relative proportion of humus and sesquioxides in the percolating moisture and also with its reaction, different kinds of podsol may be distinguished. In the more extreme types, the humus podsols, the B horizon is enriched by an accumulation of humus and sesquioxides, the accumulation of sesquioxides occurring at a lower level in the profile than that of the humus. In less extreme podsols, there may be no accumulation of humus, but an accumulation of hydrated ferric oxide in the B horizon. These are known as iron podsols. The C horizon is the parent material from which the profile is developed. The precipitation of

materials in the B horizon of podsol often leads to the formation of hardpan (ortstein). Such a condition may be followed by impedance of drainage and a change in the character of the soil profile to gley-podsol (p. 356).

The dominant factor in the development of the podsol profile is the prevalence of intense leaching owing to the continued excess of rainfall over evaporation.

Whilst podsol may be developed on all kinds of parent materials, the degree of development is affected by the base-status of the substrate and by its permeability to leaching. The most strongly developed profiles occur in quartzose sands, which are naturally poor in basic constituents. In such cases, even where the climate is not of the most extremely humid type, impoverishment rapidly occurs and the only possible type of vegetation consists of plants such as conifers and heath plants that can exist on minimal supplies of mineral plant food. With poverty in basic constituents, the residues of vegetation undergo a type of decomposition, chiefly through the action of fungi, resulting in the production of a layer of raw humus which, in the almost complete absence of earth-worms, remains sharply differentiated from the mineral soil over which it lies. The extremely acid leaching results in the development of a deep bleached layer and a humic B horizon. Such podsol may be seen on the Bagshot Sands of S.E. England. They are widespread on the sandy soils of Northern and Middle Europe.

Podsol are less readily developed in materials with high base reserves than in light quartzose sands. In loams and clays, the podsolized layer is shallower and indeed, in some cases, cannot be recognized without chemical analysis of the colloidal material. It is obvious, then, that the distribution of podsol is markedly influenced by geology. If the whole of England were a region of light sands, such as the Bagshot Beds, it would be represented on a soil map as an area of podsol. Actually, owing to the prevalence of clays and loams having notable base reserves, well developed

podsoles are by no means common. It is possible that in certain upland regions, original podsoles have been truncated by erosion consequent on deforestation in former centuries. In such areas, secondary podsoles may be developed in the original B horizon, which has been laid bare by erosion.

It is unfortunate that the available data for podsol profiles cannot be uniformly presented. Many continental and American workers have described profiles in terms of the total analyses of the individual horizons. Such figures, in the writer's opinion, are not highly instructive since they include both the unweathered skeleton of the soil and the weathering-complex, which is the seat of the chemical reactions of the soil. And thus an enrichment in sesquioxides in a given horizon, as shown by the total analyses, may either reflect the mechanical washing down of colloidal clay, or the translocation of sesquioxides from the clay complex of an eluvial horizon and their deposition in the horizon in question. The most desirable information would be in the form of chemical and mineralogical data for the composition of the clay complex in the different horizons of a profile. This information is given to some extent by certain workers who report constituents soluble in hydrochloric acid. If it could be assumed that the acid extraction used involved no attack on the unweathered minerals of the soil skeleton, such data would present a comparative view of the composition of the clay complex in the different horizons and would furnish information as to the character of the eluviation processes. Few soils, however, are free from original minerals susceptible to attack by hydrochloric acid. The error from this complication is likely to be greatest in relatively young soils. With certain tropical soils and soils whose parent materials have passed through long cycles of weathering, such as many of the Tertiary and Recent sediments, the proportion of unweathered silicates is likely to be less and the soil skeleton will consist mainly of quartz. Here the figures obtained by the use of hydrochloric acid extractions may have a real significance.

*Russia.** A sandy profile in the region of St. Petersburg (Leningrad) was described by Georgievski¹ as follows:—

Horizon A₁. Loose greyish-white layer, 4-5 inches thick.

Horizon A₂. White fine sand 10 inches or more thick.

Horizon B. A more or less compact or even hard mass of brown or black colour. In parts less cemented; thickness 5-10 inches.

Horizon C. Reddish-yellow or yellowish glacial sand.

In the same district, a clay soil gave:—

Horizon A₁. Whitish-grey fine grained layer, 5-6 inches thick.

Horizon A₂. Compact laminated almost white material, appearing white when dry and falling into a fine mealy powder. Some loam concretions present; thickness 3-5 inches.

Horizon B. Compact clayey material with abundant dark and brown concretions. The colour is mottled, whitish flecks alternating with reddish and yellowish streaks and threads of the slightly altered parent material; thickness about 8 inches.

Horizon C. Compact boulder clay of reddish-brown colour.

It will be noticed that in a heavier parent material the profile is markedly shallower. The tendency to laminated structure in the A₂ horizon is also to be noted and is a common characteristic of well developed podsoles.

It is to be presumed that, in the profiles just described, the B horizon is enriched both in organic matter and in sesquioxides. In certain sandy and gravelly profiles, the humus occurs as a distinct layer above the horizon of deposition of the sesquioxides.

Denmark. Podsol profiles under heath formation in Jutland, Denmark, have been exhaustively investigated by

*The profiles described in this and the ensuing chapters have been chosen to illustrate the distinctive features of the groups to which they belong. No attempt has been made to give examples from all countries.

In the descriptions given, the horizons A, A₁, etc., are usually given as in the papers from which they are quoted. In modern profile descriptions it is customary to use A₀₀ to denote litter, A₀ raw humus, A₁ mineral soil with humus infiltration, A₂ bleached horizon, B₁ horizon of illuvial humus deposition, B₂, B₃, etc., horizons enriched by deposition of sesquioxides. A discussion of the morphology of the horizons of the podsol profile is given by J. S. Joffe (*Soil Sci.*, 1932, **33**, pp. 217-238).



Photo

H. Morley Davies



*Photo. U.S. Dept. Agric. Soil Survey
Division.*

PODSOL PROFILES.

I.

I. Profile from Goldstone, Salop, England

II.

II. Profile in Glacial Till,
Minnesota, U.S.A.

F. Weis². Varying degrees of podsolization are reflected in the changes in the composition of the inorganic colloids extracted by the ammonium oxalate method of O. Tamm³. Marked accumulation of humus with hardpan formation is shown in the B horizons of the most strongly podsolized profiles. Sesquioxide accumulation is most marked in the humus horizon, as shown by the composition of the ammonium oxalate extract.

Sweden. K. Lundblad⁴ has described and examined a number of iron podsoles in Sweden. The following profile occurs at Siljanfors under a sparse pine wood with *Calluna vulgaris*, *Vaccinium vitis-idaea*, *V. myrtillus*, and lichens as ground vegetation :—

- A₀. 1 cm. Duff, a loose organic (F) layer.
- A₂. 7 cm. Pinkish-white bleached layer.
- B. 27 cm. Reddish-yellow, darkest at top.
- C. Morainic material mainly sandstone material with some granite.

Laboratory examination by Tamm's acid oxalate method shows an enrichment in sesquioxides and also in silicic acid in the B horizon.

S. Mattson and Y. Gustafsson⁵ have also examined Swedish podsoles from the standpoint of the former's theories of isoelectric precipitation. They find the ultimate pH to be highest in C, lower in B, and lowest in A horizons. In the B and C horizons the actual pH is below the ultimate pH.

England. W. M. Davies and G. Owen⁶ give a description of a podsol profile at Goldstone, Newport, Shropshire, developed on Bunter pebble beds under a vegetation of scrub oak, birch, bilberry, ling, heather, etc. This profile is illustrated in Plate IV. Their description is as follows :—

- A₀. 0-6 in. Leaf mould.
- A₁. 6-9 in. Greyish - black humified organic matter with bleached sand grains and numerous pebbles.
- A₂. 9-19 in. Pale grey loose sand with bleached sand grains. Numerous pebbles free of iron oxide stains.
- B₁. 19-23 in. Humified organic matter compacted.

- B₂. 23-35 in. Compact cinnamon-yellow light sand with numerous stained pebbles. Decreasing intensity of coloration with depth. Upper surface consists of $\frac{1}{4}$ " layer of cemented and lustrous iron oxide.
- C. Below 35 in. Pebbly brownish laminated and friable sandy rock.

The principal analytical data are shown in Table XXVII.

TABLE XXVII.—ANALYTICAL DATA FOR GOLDSTONE PODSOL PROFILE (DAVIES AND OWEN)

Horizon	Clay %	Organic Carbon %	pH	Composition of clay fraction		
				SiO ₂ /Al ₂ O ₃	SiO ₂ /R ₂ O ₃	Al ₂ O ₃ /Fe ₂ O ₃
A ₁ (6-9")	2.7	14.88	3.70	3.13	2.55	4.43
A ₂	1.3	1.63	3.13	2.81	2.66	18.00
B ₁	8.8	7.14	3.73	1.79	1.66	13.03
B ₂	2.2	0.40	3.75	1.51	1.19	3.80
C	3.3	0.04	4.75	2.29	1.94	5.54

The above data give a clear picture of the process of podsolization. In the first place, there is some evidence of mechanical eluviation in the rise in clay content in the B₁ horizon. Secondly, there is a marked rise in the organic carbon content in the B₁ horizon. Thirdly, the siliceous character of the clay fraction in the A horizons and the contrasted sesquioxidic character of the clay fraction in the B horizons should be remarked. Finally, the strongly acid reaction of the whole profile, and the increase in pH with depth is shown.

Scotland. Podsol profiles are of frequent occurrence in the Scottish Highlands, where they are developed under heath or coniferous forest on igneous or metamorphic parent materials. A typical example on granitic drift in Aberdeenshire is described by A. B. Stewart⁷.

The mean annual rainfall is 34 inches and the vegetation *Calluna vulgaris* dominant, with *Vaccinium myrtillus* and

Erica cinerea, and conifers replanted after de-forestation. The description is as follows:—

- (1) 0-2 cm. Surface litter.
- (2) 2-8 cm. Dark brown to blackish layer with white specks of SiO_2 ; slightly laminar in structure; plant-remains decipherable and roots abundant.
- (3) 8-18 cm. Sandy loam; light grey mineral particles and brown organic material; structureless; plastic but gritty; plant-remains decipherable and roots present.
- (4) 18-30 cm. Light brown sandy loam; friable and permeable; organic matter well decomposed; roots present; contains scattered vertical intrusions of surface material.
- (5) 30-55 cm. Dark brown, coarse, sandy loam; friable but more compact than (4); organic matter well decomposed; roots stop sharply at bottom of this layer.
- (6) 55 cm.+ Yellowish-fawn sand and gravel with horizontal rusty streaks: cemented but quite friable when broken; stones increase in quantity and size with depth.

The principal analytical data are given in Table XXVIII.

TABLE XXVIII.—ANALYTICAL DATA FOR SCOTTISH PODSOL (STEWART)

Depth (in cm.)	2-8	8-18	18-30	30-55	55+
pH	5.2	4.5	4.9	5.0	5.8
Ignition Loss ...	44.4	12.0	13.8	15.8	4.6
Clay %		5.7	10.4	5.4	1.5
Clay $\text{SiO}_2/\text{Al}_2\text{O}_3$...		2.84	2.07	1.28	1.29
„ $\text{SiO}_2/\text{R}_2\text{O}_3$...		2.46	1.44	0.91	1.04
„ $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$...		6.47	2.36	2.46	4.16

The data show some eluviation of clay and sesquioxides, but do not suggest any humus B development. The horizons to 18 cm. are of an A character, those from 18-55 cm. are B horizon, whilst below 55 cm. is C material.

Wales. The following profiles are typical.

Cefnybryn, W. Glamorgan. Altitude 300 feet. Mean

annual rainfall, 40 inches. Mean annual temperature, 50°F. Parent material, Old Red Sandstone Conglomerate. Vegetation, *Ulex spp.*, *Festuca spp.* (described by D. O. Hughes and Brynmor Jones⁸).

Horizon	Depth		Organic Carbon %	pH
A ₀ .	0-4 in.	Fibrous peat layer ...	—	—
A ₂ .	4-7 in.	Greyish sand ...	1.61	4.6
B.	7-12 in.	Reddish-brown sandy loam ...	2.08	4.7
C.	14-16 in.	Yellowish-brown sandy loam on rock ...	0.48	5.5

The composition of the clay fraction in the several horizons is as follows:—

Horizon	SiO ₂ /Al ₂ O ₃	SiO ₂ /R ₂ O ₃	Al ₂ O ₃ /Fe ₂ O ₃
A ₂ .	3.70	3.33	9.09
B.	2.44	1.67	2.17
C.	2.80	2.03	2.63

The data indicate a slight accumulation of organic matter and alumina and a marked accumulation of ferric oxide in the B horizon.

Aber, Caernarvonshire. Altitude, 900 feet. Mean annual rainfall, about 60 inches. Mean annual temperature, 47°F. Parent material, Ordovician shale. Vegetation, *Calluna vulgaris*, *Vaccinium myrtillus*, *Festuca spp.*, *Lichens*. (Described by G. H. Gethin Jones⁹.)

Horizon	Depth		Organic Carbon	pH
A ₁ .	0-5 in.	Dark peaty layer ...	13.8	3.6
A ₂ .	5-8 in.	Grey stony loam ...	6.2	4.1
B ₂ .	8-14 in.	Reddish-brown loam ...	4.7	4.7
B ₃ .	14-20 in.	Light brown shaly loam ...	3.5	4.7
B ₄ .	20-26 in.	Light brown very shaly loam	3.6	4.8

The composition for the clay fraction in the several horizons is as follows:—

Horizon	SiO ₂ /Al ₂ O ₃	SiO ₂ /R ₂ O ₃	Al ₂ O ₃ /Fe ₂ O ₃
A ₁ .	4.40	3.56	4.24
A ₂ .	3.84	2.75	2.52
B ₂ .	1.90	1.31	2.22
B ₃ .	2.09	1.39	1.99
B ₄ .	1.56	1.17	3.00

The data give no indication of accumulation of organic matter, but clearly show the deposition of ferric oxide and, to a smaller degree, alumina in the B horizons.

United States. Podsoles are of frequent occurrence throughout the more humid regions of the Northern United States and Canada. A profile collected by W. J. Geib¹⁰ near Bayfield, Wisconsin, is described as follows:—

- A₀. 0-3 in. Dark brown decayed leaves and other organic matter.
- A₁. 3-8 in. Grey with very slight pink tint.
- B. 12-30 in. Light to dark coffee brown, compactly cemented.
- C. 30-40 in. Pinkish-grey resting on heavy red clay.

The profile is developed in a fine sandy loam and shows a definite accumulation of clay in the B horizon. The silica-sesquioxide ratios of the colloidal clay in the successive horizons are 3.76, 4.01, 1.59, and 2.40 respectively.

W. J. Latimer¹¹ describes the following profile from Washington, Massachusetts:—

- A₀. 0-6 in. Dark brown with mould and roots.
- A₁. 6-11 in. Essentially grey, but containing brown spots.
- B₁. 11-13 in. Dark brown or coffee coloured.
- B₂. 13-24 in. Yellowish-brown to pale yellowish-brown.
- C. 24-36 in. Yellowish-grey and streaked mottled brown.

The texture is a loam and increases in heaviness in the B and C horizons. The B₁ horizon shows an accumulation of organic matter. The silica-sesquioxide ratios of the colloidal clay in the successive horizons are 2.16, 2.74, 0.86, 1.28, and 1.67, respectively.

M. M. McCool, J. O. Veatch, and C. H. Spurway¹², in studies on soil profiles in Michigan, have given the following generalized description of podsolized soils from the northern part of the State.

1. Thin humous soil (mould).
2. Grey podsolized soil (3-24 in.).
3. Brown horizon (dark coffee brown to light leather colour and dull yellow); thickness 4 in. to 4 feet; horizon of acid concentration.
4. Horizon showing iron oxide coloration; highest clay content; gradation to substratum.
5. Substratum.

H. A. Lunt¹³ gives a description of New England soils under different types of forest vegetation and humus cover. They are generally of the iron podsol type and the degree of development is closely correlated with the type of humus cover. A Minnesota podsol is shown in *Plate IV*.

Tropics. It was formerly considered that podsoles were confined to temperate and cold humid regions. According to P. Vageler¹⁴, however, podsolization can occur to some extent in the tropics under conditions of extreme humidity. H. J. Hardon¹⁵ has described certain soils in S.E. Borneo, known as *padang* soils, which are definitely podsoles. They occur at about 90 metres altitude under 3,000 mm. annual rainfall, and mean annual temperature 26°C. The vegetation is of a heathy type and the parent material is a very coarse sand. The following is a typical profile.

- A₀. 0-20 cm. Brown-black layer of semi-decomposed plant residues intermixed with coarse quartz sand.
- A₁. 10-25 cm. Loose greyish-black humic quartz sandy layer.
- A₂. 25-40 cm. Loose greyish-white quartz sandy layer.
- B₁. 40-70 cm. Dark brown very compact quartz sandy hardpan.
- B₂. 70-100 cm. Loose light brown quartz sandy layer.

The silica-sesquioxide ratios of the clay in the horizons are as follows:—

A ₀	A ₁	A ₂	B ₁	B ₂
3.62	7.17	8.64	0.42	0.31

TRUNCATED PODSOLS

In hilly districts, soils are frequently encountered in which the A horizon has apparently been removed by erosion. G. W. Robinson¹⁶ describes such a profile at Aber, Caernarvonshire. It occurs under grass and bracken under a mean annual rainfall of 60 in. at 800 feet.

- 0-3 in. Turfy layer.
- 3-6 in. Dark brown turfy loam.
- 6-9 in. Brown loam.
- 9-12 in. Light brown, light loam.
- 12-15 in. Reddish-brown shaly loam on Ordovician shale.

The principal analytical data are shown in Table XXIX.
TABLE XXIX. — ANALYTICAL DATA FOR TRUNCATED PODSOL

Depth	0-3 in.	3-6 in	6-9 in	9-12 in.	12-15 in.
Organic carbon % ...	15.9	8.1	5.4	3.4	
pH	4.20	4.42	4.58	4.78	4.82
Clay fraction : $\text{SiO}_2/\text{Al}_2\text{O}_3$	2.17	2.25	2.17	1.95	2.12
„ „ $\text{SiO}_2/\text{R}_2\text{O}_3$	1.63	1.69	1.62	1.48	1.50
„ „ $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$	3.02	3.02	2.95	3.13	2.42

The B character of the surface soil may be even more pronounced in other examples. $\text{SiO}_2/\text{R}_2\text{O}_3$ ratios of less than 1.0 have been recorded at higher altitudes.

VARIATIONS IN PHYSICAL PROPERTIES IN PODSOL PROFILES

The vertical variation in the physical properties of podsol profiles is governed by the texture of the parent material, the degree of development of the profile, and the thickness of the peaty layer. A. F. Lebedev and E. E. Bankova¹⁷ have followed the vertical changes in a number of physical constants, including volume weight, porosity, and maximum molecular water-holding capacity for representative profiles. In general, the volume weight increases with the depth, but whilst in some cases it reaches a maximum in the B horizon, in other cases there is a continuous increase from the surface to the C horizon. The variations in porosity are generally in the opposite direction, a minimum occurring sometimes in the B, sometimes in the C horizon. Maximum molecular water capacity may increase with depth, and pass through a maximum in the B horizon or, in the case of humus podsoles, show a maximum in the upper A horizon.

There is generally a certain amount of mechanical eluviation in podsol profiles. The accumulation of colloidal material in the B horizon is most marked in soils of light

texture. This accumulation may be so pronounced in some cases as to lead to a certain amount of impedance of drainage with consequent waterlogging—a condition encountered in some of the podsol soils of the Bagshot area of Surrey. The development of an horizon with restricted permeability is doubtless a factor in the precipitation of sesquioxides and the development of a pan. At a certain stage of development of pan the restriction of drainage may be sufficient to change the character of the profile and gley podsoles may be formed, passing ultimately into peat podsoles and peats.

The degree of induration of the B horizon varies considerably. In some cases, although there is a definite horizon of accumulation, induration is only slightly developed. At the other extreme are rock-like B horizons such as occur in the Bagshot profiles. A pebbly or stony texture appears to favour the formation of highly indurated illuvial horizons.

In podsoles developed from substrates of heavier texture, such as the shaly loam profiles of Wales, mechanical eluviation is less marked and the induration in the B horizon is comparatively slight.

MECHANISM OF PODSOLIZATION

We have already seen that podsolization is a consequence of the removal of bases by leaching and the development of an acid organic layer at the surface. Sulphuric acid formed by the biological oxidation of organic sulphur compounds may also play a part in the leaching processes (cf. p. 218). With regard to the mechanism of the process, some difference of opinion exists. The accumulation of sesquioxides in the B horizon may reflect either a translocation and deposition of clay, which, relative to the coarser fraction of the soil, is rich in these constituents, or an actual differentiation of the clay complex due to a simple translocation of sesquioxides from the A to the B horizons. Whilst it is certain that in some cases mechanical eluviation, resulting in an actual transference of inorganic colloidal material from

the A to the B horizon, takes place, the differences found in the composition of the clay complex in the several horizons by certain workers can only be explained by postulating a chemical eluviation.

The translocation and deposition of humus occurs only under very acid conditions. B. Aarnio¹⁸ has studied the mutual precipitation of humus and sesquioxide sols and finds that with ferric oxide-humus ratios varying from 1:0.2 to 1:2.8, precipitation occurs. The corresponding range for mutual precipitation of humus and alumina sols is 1:1 to 1:30. It can thus be seen that ferric oxide is more mobile in the soil profile than alumina, for when humus is in excess in the soil solution, at least 30 times as much humus as alumina must be present for this constituent to pass into colloidal solution. A more moderate concentration of humus suffices to ensure the translocation of colloidal ferric oxide. It is to be presumed that sols having the sesquioxides in excess of the humus do not occur under ordinary conditions. Assuming a sufficient solubility of the humus to give a humus-alumina ratio of over 30, then a decrease in this ratio owing to the removal of some of the humus will result in a mutual precipitation of the humus and alumina. Sufficient humus will remain in solution to protect the ferric oxide, which will be precipitated at lower levels.

The differentiation of the clay complex implied by the variations in its composition in the horizons of a normal podsol profile is generally held to be a consequence of its instability under conditions of base-unsaturation. Where there is base-saturation, the clay complex remains stable and no differentiation occurs. An essential for podsolization is the presence of raw humic matter such as occurs under coniferous forest or heath. It would appear that an acid reaction is not in itself sufficient to cause podsolization. This may be readily shown in the laboratory by allowing 0.1 *N*-solutions of hydrochloric acid and oxalic acid, respectively, to percolate through ferruginous sand. Although the pH of the hydrochloric acid is lower than

that of the oxalic acid, the solvent action of the latter acid is considerably greater and quickly leads to a bleaching by removal of ferric oxide. H. T. Jones and J. S. Wilcox¹⁹, from laboratory studies of the solution of sesquioxides in A horizons and their precipitation in B horizons, conclude that hydroxy-acids play a part in the solution of sesquioxides, which are translocated in combination as complex anions and precipitated as basic salts. P. H. Gallagher²⁰ considers that the effective agent in podsolization is not the hydrogen ion but the associated anions principally of hydroxy-acids and oxalic acid formed by the decomposition of plant residues. According to this view acidity is not necessary for podsolization, although it is almost invariably present. Certain Irish podsol soils have been found to occur with neutral reaction and high base-status.

The deposition of sesquioxides removed by leaching from the A horizon in podsol profiles has not yet been completely explained. There is generally an increase in base-saturation with depth, and this in itself would lead to some deposition of constituents which have been brought into solution by acid percolating waters. There is also the possibility that accumulation of sesquioxides may result, in part, from the restriction of free percolation in an horizon enriched in clay by mechanical eluviation.

C. G. T. Morison and D. B. Sothers²¹ consider the deposition of ferric oxide in iron pans to be due to irreversible precipitation of iron from humus-protected iron sols during periods of drought. During the winter months, the movements of soil moisture are mainly downwards and this results, if there is a surface layer of acid humus, in a downward leaching of ferric oxide, and, possibly, of alumina, in colloidal solution. With the drying out of the profile during summer, precipitation occurs. The localization of this precipitation in a definite horizon is possibly connected with the course of the moisture gradient. It is known that capillary movement becomes negligible at moisture contents in the vicinity of the moisture equivalent. Morison and

Sothers consider the horizon of precipitation to be determined by the proximity of a level of complete saturation, but it does not appear possible to postulate a water-table so near the surface. The horizon of deposition may occur at a depth where the subjacent strata are sufficiently moist to furnish a supply of precipitable material by capillary rise.

This view of the deposition of sesquioxides may apply also to the deposition of humic material. If it is correct, the B horizons are developed by precipitation not from descending solutions during periods of leaching but from ascending solutions during periods of drought.

The rate of podsolization varies enormously with climate, parent material and vegetation. It is not, however, a process requiring "geological time." O. Tamm³ estimates that in N. Sweden, under Scots pine, 1-2 cm. of bleached layer is formed in a century.

An exhaustive discussion of the process of podsolization is given by J. S. Joffe²². S. Mattson and Y. Gustafsson²³ have discussed podsolization from the standpoint of the former's iso-electric complex theory.

CRYPTOPODSOLIC SOILS

The term *cryptopodsols*, as distinct from *phaneropodsols*, is used by C. C. Nikiforoff²¹ to describe soils in which the podsolic character is demonstrable only by chemical analysis. The soils represent a transition to the soils described in the next section in which sesquioxide translocation is recessive. They occur abundantly in Wales and are characterized by a dark humus A horizon overlying a B horizon which is generally yellowish or orange-brown in colour. Examination of the clay fraction reveals a definite increase in sesquioxides in passing from A to B. On oxidizing with hydrogen peroxide to destroy humus it is generally observed that the A horizon is somewhat greyer in colour than the B horizon. The slight podsolization is therefore masked by the humus colour.

The following profile may be cited as an example of soils of this class:—

Mynytho, W. Caernarvon, Wales. Altitude about 250 feet. Mean annual rainfall 40 inches. Mean annual temperature 50°F. Parent material porphyritic rhyolite. Grassland vegetation. Drainage free.

- I. 0-8". Dark greyish-brown rather stony light loam.
- II. 8-12". Bright yellowish-brown rather stony light loam.
- III. 12-18". Pale yellowish-brown rather stony light loam.
- IV. 18" +. As above but more stony, passing to rock brash.

The following are the principal analytical figures:—

	Clay %	Organic Carbon	pH	SiO ₂	Al ₂ O ₃	Clay SiO ₂ /K ₂ O ₃	Al ₂ O ₃ /Fe ₂ O ₃
I.	18.3	3.55	5.51	2.57	1.93	3.01	
II.	18.6	1.43	5.28	2.16	1.62	3.00	
III.	15.0	0.53	5.40	2.17	1.72	3.82	
IV.	14.0	0.22	5.51	2.67	2.09	3.60	

The figures for the composition of the clay fractions reveal a definite accumulation of sesquioxide in layers II. and III.

The Spanish soils described by E. H. Del Villar²⁵ as *acid-humic* soils would appear to fall into the cryptopodsol class for the bleaching in the A horizon, if present, is masked by humus accumulation.

BROWN EARTHS OR GREY-BROWN PODSOLIC SOILS

The name *brown earths* (Braunerde) was applied by Ramann to a group of soils occurring in Western Europe and developed naturally under deciduous forest. They are also known as *brown forest soils* and appear to correspond with the grey-brown podsolic soils of the United States. Soils of a character generally similar to the brown earths of Europe occur in many parts of the world and the attempts to correlate them have given rise to considerable discussion on the definition of the group. The following appear to be the essential characters of the great world group of which the brown earths or brown forest soils found in different parts of the world are **variants**.

(1). The profile is completely leached of carbonates. Carbonates may be present in the C horizon, or in the top soil as residues from added dressings. Drainage is free.

(2). The colloidal complex is not highly base-unsaturated and the reaction is only moderately acid.

(3). The humus is of the "mild" type, well distributed throughout the upper horizons without any tendency towards the development of a raw humus layer.

(4). The composition of the clay complex in soils of primary weathering tends towards a $\text{SiO}_2/\text{R}_2\text{O}_3$ ratio of 2.0, representing a stage in desilicification intermediate between that of the chernozem group and that of the ferrallitic soils of the tropics.

(5). Free sesquioxides are present, and the hydrated ferric oxide thus occurring gives a brownish or reddish-brown colour, which may be masked by humus.

(6). There is no differential eluviation of silica or sesquioxides and the $\text{SiO}_2/\text{R}_2\text{O}_3$ ratio of the clay remains fairly constant down the profile.

(7). The soil structure is moderately granular.

(8). The natural vegetation is deciduous woodland or scrub.

The affinity of these soils with the podsols consists in the complete leaching of carbonates from the mature soil profile and the development of a brown colour suggestive of the B horizon of the podsols. They differ from the podsols in some important respects, but chiefly in their better base-status. This may be due to either or both of two causes. On the one hand, the climate may be such as to involve a less intense leaching, whilst, on the other hand, the parent material of the soil may be sufficiently rich in basic reserves to oppose the extreme impoverishment which favours podsol development.

The return to the soil of leaf-fall containing basic constituents is a powerful factor in maintaining the base-status of these soils in their virgin state. The presence of a ground-vegetation also assists in promoting the circulation of mineral

nutrients through a deep layer of soil and subsoil. The soil under deciduous forest maintains a population of earthworms, which are the most important agents in distributing organic matter throughout the layers which they occupy. And thus, whilst the organic matter profile under conifers consists of a sharply defined raw humus layer, overlying a mineral soil relatively poor in organic matter (although sometimes including a humus B horizon), the organic matter of the soil of a deciduous forest shows a fairly uniform distribution throughout the top foot or eighteen inches, decreasing gradually in deeper layers. An accumulation of organic matter in a B horizon such as occurs in the humus podsoles is never found in the brown earths.

The marked translocation of sesquioxides, which is betokened by the bleaching of the A horizon and the brown or reddish-brown coloration of the B horizon in podsoles, is nearly or completely absent in the brown earths, where bleaching is scarcely shown. Apart from mechanical translocation, the clay complex remains comparatively unaltered throughout the profile.

A. Stebutt²⁶ considers that, in the brown earths, the clay complex has undergone a certain degree of degradation into its constituent silicic acid and sesquioxides. The brown colour of these soils is an evidence of the presence of free hydrated ferric oxide. A further stage in the degradation process consequent on impoverishment in bases would involve the differential leaching out of the sesquioxides and the development of a bleached A horizon as in the podsoles.

Structurally, the brown earths show important differences from the podsoles. Whilst in the A horizons of podsoles the single grain structure predominates, the brown earths are generally distinguished by a crumb structure or a variant of this structure. This may be attributed to the better base status and to the better distribution of base-saturated organic matter, throughout the soil layers.

It should be added that all gradations are possible from podsoles to brown earths, and it is thus possible to describe

certain soils as slightly podsolized brown earths. The brown podsollic soils of the United States would appear to form a transition between brown earths (grey-podsolic) and podsoles.

Sweden. The character of the brown earth profile is illustrated by the following Swedish profile described by K. Lundblad²⁷. It was found under beechwood.

- A₀. Beech litter, 2-3 cm. thick.
- A₁. Loamy layer containing mild humus with indefinite lower limit. Thickness 12-15 cm.
- B. Brown earth. Thickness 40 cm.
- C. Sandy, stony, moraine, principally of granite material.

England. W. M. Davies and G. Owen⁶ give the following description of a brown earth in Shropshire:—

- 0-9 in. Brownish-red, loamy sand. Crumbly and somewhat gravelly.
- 9-18 in. Similar material, but rather more compact. Gravelly.
- Below 18 in. Disintegrated lavender coloured sandstone, passing into a layer of purplish-red marl at 40 in.

The principal analytical figures are shown in Table XXX.

TABLE XXX.—ANALYTICAL DATA FOR SHROPSHIRE BROWN EARTH (DAVIES AND OWEN)

Depth	0-9 in.	9-18 in.	Below 18 in.
pH	4.77	5.10	5.34
Clay, %	16.3	17.5	15.3
Ignition loss % ..	4.95	3.28	3.00
Clay (SiO ₂ /Al ₂ O ₃)	2.44	2.48	2.54
„ SiO ₂ /R ₂ O ₃	2.06	2.04	2.07
„ Al ₂ O ₃ /Fe ₂ O ₃	5.42	4.86	4.40

The profile is somewhat more acid than is usual in brown earths. The constancy in composition of the clay fraction should be noted. No figures for organic carbon are given, but the ignition loss suggests low figures.

The profile described above is probably typical, in its essential features, of large areas of similar soils in England

and Wales, and may be expected in well drained situations with parent rocks of moderate base-status under British climatic conditions. Where, as in certain coarse sands, notably in the Trias, the base reserves are poor, podsoles are developed. It is thus possible for brown earths and podsoles to occur under exactly similar climatic conditions, the difference in the final result being due to the nature of the parent material.

Wales. The characters of a Welsh brown earth profile are shown in the following description:—

Llanfairpwll, Anglesey. Altitude, 120 feet. Mean annual rainfall, 38 inches. Mean annual temperature, 50°F. Parent material, Pre-cambrian schistose drift. Artificial grassland, but originally deciduous forest.

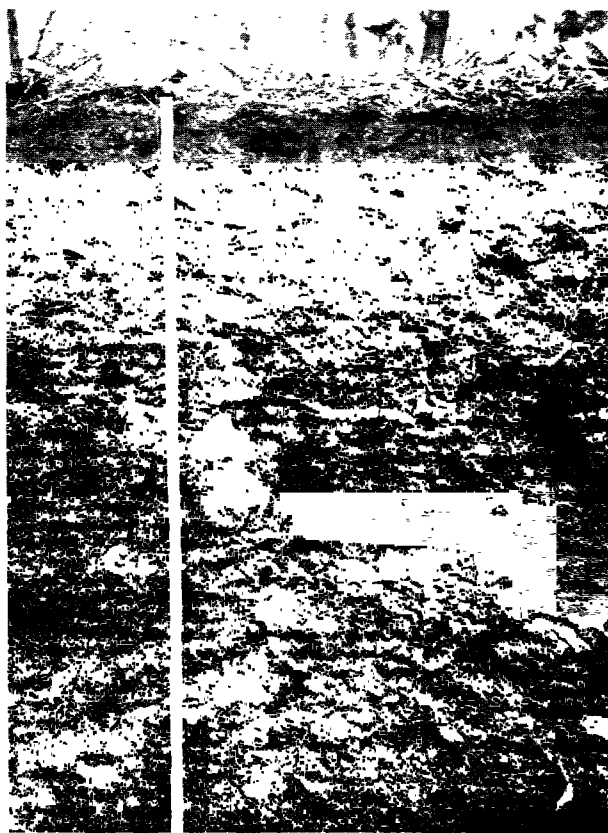
Horizon	Depth	Description	Clay	Organic Carbon	pH
I.	0-9 in.	Dark brown stony loam . .	18.7	2.9	5.40
II.	9-15 in.	Brown stony loam . .	20.0	2.05	5.64
III.	15-36 in.	Reddish-brown stony loam	16.9	1.1	5.94
IV.	36-48 in.	Yellowish-brown stony loam	n.d.	nil	5.80

There is no well marked differentiation between A, B, and C horizons. The variations in the composition of the clay fraction are shown in the following table:—

Horizon	SiO ₂ /Al ₂ O ₃	SiO ₂ /R ₂ O ₃	Al ₂ O ₃ /Fe ₂ O ₃
I.	2.39	1.80	3.05
II.	2.47	1.85	2.99
III.	2.41	1.80	2.95
IV.	2.64	2.05	3.47

These figures exhibit a reasonable constancy in composition of the clay fraction in the first three layers. The fourth layer may well represent C horizon material. So far as an A horizon is concerned, either it has been removed by erosion or else it has been mixed by cultivation with the B horizon. Neither the field characters nor the laboratory data offer any evidence of an eluviated horizon.

N.IV. Europe and N. America. Brown earths occur commonly over a large area of Western Europe. They



[Photo. C. E. Killogg.]

GREY-BROWN PODSOLIC SOIL, TENNESSEE.

occur also in the Eastern United States from New York to N. Carolina. The American brown earths, or grey-brown podsollic soils, often show a marked development of a texture profile due to the mechanical eluviation of clay and fine material from the surface horizons. From the data available it would appear that there is no marked difference in the composition of the clay fraction in the different horizons, as would be the case if chemical eluviation had been operative. The removal of clay from the surface horizons does, however, produce a weakening of the soil colour in the top soil, so that many of these soils appear somewhat bleached. It should be added that in many districts there has been extensive sheet erosion, with the result that the original B horizon is now exposed, and in many cases forms the cultivated soil.

J. Geering²⁸ has described the development of brown earths on soft limestone (molasse) in Switzerland. Basing his discussion on the composition of the clay fractions in the profile, he proposes the use of a quotient obtained by dividing the clay $\text{SiO}_2/\text{R}_2\text{O}_3$ ratio in the A horizon by the corresponding ratio in the B horizon. In the profiles examined by him this quotient varies from 1.0-1.1, whilst in podsols the corresponding figures are 2.5-4.9.

BRITISH AGRICULTURAL BROWN EARTHS

Most of the soils of Great Britain with good natural drainage were probably brown earths under primitive conditions, but owing to their long agricultural history, they must be regarded as highly artificial. The original deciduous forest that covered most of the country has been almost entirely removed and authentic natural profiles can be studied only in isolated localities such as the Forest of Dean, the New Forest, and the Forest of Wyre. It is to be regretted that, at present, no data are available for profiles in these areas.

Under ordinary farming conditions, the incorporation of organic matter with the soil by the addition of farmyard manure and by the cultivation of artificial grass leys, and the

maintenance of the base-status by chalking, liming, or marling, have tended to modify the original brown earth soil and produce a type of soil which in some respects resembles the prairie soils to be discussed below.

We have seen that brown earths are developed under deciduous forest and that the relatively high mineral content of the leaf litter and the presence of a gramineous and herbaceous ground vegetation maintain the base-status of the soil and oppose podsolization. Where the natural deciduous forest is removed and the soil is afforested with conifers, it may happen that deterioration in base-status proceeds to such a degree as to result in incipient podsolization. This may be seen in plantations on light soils in England, for example, in the Delamere Forest of Cheshire. Similar deterioration takes place where natural deciduous forest becomes replaced by heath. Podsolization is a deteriorative change, and it is important to realize that, on light soil under heavy rainfalls, the change from brown earth to podsol may easily follow the removal of deciduous forest. G. Lemée²⁹ has described the degeneration by podsolization under *Calluna* of certain soils in the Perche district of France, formerly under oak forest. The parent material is quartzose sand.

PRAIRIE SOILS

The podsoles and their congeners are for the most part developed under forest. Beyond the forest limit to the north lie the tundras (Chapter XII), where, although the humidity is moderate or excessive, the general rigour of the climate precludes forest growth. There is an important group of soils, termed *prairie soils*, lying on the arid side of the eastern forest belt of the United States and occupying a considerable proportion of the so-called Middle-West. These soils, although developed under steppe or prairie conditions, appear to belong to the great group of humid soils rather than to the arid soils, which lie adjacent to them and are also developed under steppe conditions. To the east of the prairie belt occur the podsoles in the north, the brown earths (grey-

brown podsollic soils) in the middle, and the red and yellow podsollic soils (Chapter XIV) in the southern states. The rainfall under which the prairie soils occur is sufficient to produce a complete leaching of soluble salts, including carbonates, in the soil profile, and there is thus no horizon of accumulation of calcium carbonate or gypsum as in the neighbouring chernozems (see Chapter XI). Calcium carbonate encountered in a prairie profile belongs to the C horizon and is to be reckoned with the parent material. A characteristic prairie soil profile consists of three horizons, namely, a dark coloured horizon rich in organic matter, a transition horizon often showing brown colours, and the underlying parent material, which is generally of a grey colour. Calcium carbonate is found at a depth of 50-60 cm. where, as is frequently the case, the parent material is a calcareous loess.

The following profile, developed on loess in Houston Co., Minnesota, is described by A. L. Gray, *et al*³⁰.

- 0-9 in. Very dark greyish-brown mellow silt loam, nearly black when moist. Granular throughout and laminated. Grey specks in upper 5-6 inches, more noticeable in lower 3-4 inches.
- 9-19 in. Greyish-brown very granular silt loam. Granules larger than in first layer. Laminated granules noticeably grey coated.
- 19-30 in. Light brown silt loam with large aggregates, tending to blocky structure, slight lamination in upper 1-2 inches. Grey coatings on aggregates. Some organic material on surface of aggregates. "Abandoned worm and insect channels abundant."
- 30-49 in. Parent material with transitional layer in top 6 inches. Yellowish-brown silt loam with no noticeable structure. Some light grey mottling in lower 8-9 inches.

The granular structure is not so marked as in the chernozems and may be entirely lacking, whilst the calcium carbonate in the C horizon is quite distinct from the concretionary deposits found in the more arid soils.

The prairie soils resemble the chernozems in their organic matter profile. The abundant and deep rooted grass vegetation, the presence of a rich soil fauna, and, in spite of

the leaching of calcium carbonate, the favourable base-status, all result in a deep enrichment of the soil in dark-coloured base-saturated organic matter.

Eluviation of sesquioxides and deposition in a B horizon does not occur. It may be conjectured that the clay complex in prairie soils has scarcely suffered to any appreciable extent that degradation into free silicic acid and sesquioxides which Stebutt postulates for the brown earths. The dark colours of the prairie soils mask field evidence of changes affecting the inorganic complex, but incipient degradation is sometimes shown by the presence of brownish colorations below the dark coloured horizon.

It should be added that H. Stremme³¹ and certain other continental writers consider the North American prairie soils as "meadow" or "gley" soils (see Chapter XI), whose distinctive characters are due to the presence of groundwater. On the other hand, N. Florov³² assigns these soils to the class of degraded chernozems (see opposite). The American workers class them definitely with the humid soils and relate them to the podsol group. It is considered that the prevalence of steppe rather than forest conditions is due to the prevention of natural regeneration through grazing animals and prairie fires. It is certain that, since the extinction of the herds of bison, and the prevention of fires by settlement, forest vegetation has tended to invade these regions, and it may be reasonably conjectured that, in the absence of interference, the prairie soils would undergo a kind of degradation analogous to that exhibited in the forest soils bordering on the chernozem regions of Russia. (See below.)

Prairie soils doubtless occur in many parts of the world on the humid side of the boundary between the humid and arid soils. Economically, they must rank among the most fertile of the great groups, and their recognition and definition is an important task for the future.

There is a class of soils occurring in the humid west of Britain that may be considered to have some affinities with the prairie soils. These are the soils of permanent grass-

lands. The resemblance consists in their high content of organic matter well distributed throughout the soil profile. But, inasmuch as, except on calcareous soils, their base-status is often low, the type of organic matter formed by micro-biological decompositions will be greatly different, being of a less marked black colour. Further, the clay complex under such conditions is less stable than in the prairie soils and may undergo degradation, as in the brown earths, or even differentiation, if the profile is sufficiently acid to permit podsolization.

DEGRADED CHERNOZEMS

We have seen that the prairie soils of N. America occur in a belt between the forest soils (podsoils, etc.), and the chernozems to be described in the next chapter. In Europe their place is occupied by a group of soils termed *degraded chernozems* or grey forest soils. It is considered that the region occupied by these soils represents former steppe and that the profiles found there have certain surviving characteristics of the chernozems.

In the first stages of degradation under forest, the changes are mainly structural and consist in the destruction of the characteristic porous crumb structure of the chernozem. There is also a sinking of the calcium carbonate horizon and some loss of organic matter. In a more advanced stage of degradation, there is a further obliteration of the porous structure and the development of a mineral profile, characterized by eluviation and deposition of sesquioxides and the disappearance of carbonates from the profile, resulting in the formation of the so-called *grey forest soil*.

The following data by Georgievski are quoted by Glinka³³ for a grey forest profile from the Poltava government:—

A₀. 0-2.5 or 5 cm. Forest litter.

A₁. Dark brown to light grey granular layer, the granules increasing to walnut size, down to 26 cm., where there is a change to

- A₂. Ash grey horizon with nut structure. On drying, breaks up into small angular blocks with greyish-white powdery coating. The thickness of this horizon is 47-48 cm.
- B₁. Reddish-brown compact loam at first containing organic matter and showing nut structure. Dark brown deposit in pores and cracks. The thickness of this horizon is 70-140 cm.
- B₂. Brownish, highly calcareous loam sometimes passing into hard white marl. Thickness 70-140 cm.
- C. Yellow loess.

A transition occurs to typical podsol soils on the side of increasing humidity.

The decisive feature of the degraded chernozems or grey forest soils is the development of a brown or reddish-brown colour in the subsoil horizons, indicating the operation of podsollic eluviation. The decrease in organic matter content compared with adjacent black earths has been shown by numerous analyses. It appears, however, that the organic matter profile shows a more gradual decrease of this constituent with increasing depth than in the typical podsols.

The Russian workers have recognized a number of stages in the degradation of chernozems, ranging from the unchanged chernozem to definite podsollic forest soil with markedly bleached horizons below the forest litter. H. Stremme⁴⁴ and others have described soils in Germany which appear to belong to the class of degraded chernozems. Examples are given by C. E. Kellogg⁴⁵ from Wisconsin, where grey forest soils appear to have developed from former prairie soils. M. Popovât⁴⁶, in Rumania, has described the successive gradations from chernozem through degraded chernozem to brown-red forest soil in the Dolj district. The parent materials are diluvial clay or loessial loams. The brown-red forest soils are probably akin to the N. American red podsollic soils. Degradation of the chernozem is marked by incipient eluviation and development of an illuvial B horizon. This is accompanied by a sinking of the calcareous horizon and fall of base-status, accentuated in the final brown-red forest soil stage.

MOUNTAIN SOILS

The soils of alpine regions resemble soils of high latitudes, principally in the circumstance that, owing to the prevalence of low temperatures, weathering is mainly of a physical character. Apart from the low temperatures under which they are developed, the most important factor affecting them is the strong relief, which facilitates erosion and, except in valleys, prevents the accumulation of deep layers of weathered material.

Generally speaking, there is a high precipitation in mountain regions. This is not invariably the case, and it may also happen that the rainfall does not increase uniformly with altitude, but passes through a maximum at intermediate altitudes. The humid character of mountain regions favours intense erosion, and the soils on hillsides are generally thin, whilst valleys, if not occupied by glaciers, are deeply filled with the spoil of the higher lands. The intense leaching results in removal of bases so that soils are generally acid in character. H. Jenny³⁰ found that, even on calcareous rocks, about 80% of alpine soils examined in Switzerland were actually acid. The acid character of the soil and the low temperatures which prevail favour the accumulation of peaty organic matter, the so-called alpine humus, in folds and hollows. Generally, however, erosion prevents the accumulation of more than about 4 inches of rocky humus soil.

The relief is generally the most important factor in differentiating soils of mountain regions. Thus, whilst in exposed situations the soil may be represented by bare rock or spreads of angular rock fragments, on gentle slopes and shelves there may be a sufficient depth of soil to carry a closed association of grass or, at lower elevations, forest.

Alpine humus soils occur above the level of forest. Whilst humidity generally increases with altitude, at great elevations, maximum humidity is passed and a decrease sets in. This decrease may in some cases determine the recession of forest growth and the prevalence of grass vegetation. In other cases, the limit may be imposed by the rigour of the

climatic conditions. The height at which forest soil or its successors gives place to alpine humus varies with latitude. In Britain the limit may lie at about 2,000 feet, whilst in equatorial regions it may be as high as 13,000-14,000 feet.

In a study of the soils of a mountain area in N. Wales, G. W. Robinson and T. Wařowicz³⁷ found podsols and humus podsols up to nearly 3,000 feet, with alpine soils on the highest peaks. Truncated soils were also found with surface soils of strongly marked B character.

The profile of alpine humus soils is relatively simple and consists of a layer of humus soil overlaying rock. The thickness is variable but generally small. The organic matter content varies considerably. Whilst in some cases the soil may consist entirely of a felt of fibrous peaty matter, in other cases only a few per cent. of organic matter is present.

The vegetation of alpine humus soils is of a decidedly xerophilous character. The conditions, however, differ markedly from those obtaining in deserts, for the adaptation is not to predominantly arid conditions but to strongly variable conditions, which include periods of intense drought. The drought is intensified by the thinness of the soil, the prevalence of high winds, and the strong insolation. Xerophytic characters can be observed also in heath vegetation at lower altitudes.

The soils in wet hollows at high altitudes are naturally of a peaty character. Thick layers of peat may be developed where slopes are maintained constantly wet by surface water.

Alpine soils are generally dark in colour owing to the presence of organic matter. The colour of the mineral soil is generally grey. Owing to the low temperatures, there is no chemical weathering and thus no formation of colloidal clay to undergo degradation as in the podsols. Whilst clay of primary origin is not likely to occur in high alpine regions, it may happen that, where the parent rock consists of unmetamorphosed sediments, soils containing colloidal clay will occur and podsolization may be expected.

Owing to their inaccessibility, comparatively little is known as to the conditions of soil formation at high altitudes. The altitude at which the distinctive characters of mountain soils occur varies, of course, with latitude, and whilst in Central Africa these characters are seen only near the peaks of the highest mountains, in high latitudes they are encountered at comparatively low elevations. Indeed, it might be thought that the principal distinction between alpine soils and the tundra soils of high latitudes consists only in the nature of the relief forms. The important difference consists in the much more intense solar radiation in equatorial regions. The exact consequences of this remain to be elucidated.

PODSOLIC SOILS WITH HIGH BASE STATUS

It is customary to think of podsoles as developed under extremely acid conditions and indeed to regard acidity, i.e., a relatively high hydrogen-ion concentration as a condition of their formation. It is possible, however, as suggested by P. H. Gallagher³⁸, that the effective agent in podsolization is not the hydrogen-ion but the anions of organic acids, formed by the decomposition of plant residues. P. H. Gallagher and T. Wálsh³⁹ have described podsolie soils, termed by them grey-brown soils, developed in calcareous drift in Co. Kildare, Eire. Whilst the grey horizons and the underlying brown horizons are suggestive of podsoles, the reaction of the solum is on the alkaline side of neutrality. The characteristic superficial layer of raw humus is also lacking. Yet the ratios for the clay fractions confirm the impression obtained from the field characters that there has been a translocation of sesquioxides from the A to the B horizon. A similar profile is described from Co. Roscommon.

In many parts of N. America there are soils under mixed deciduous and coniferous tree cover which resemble podsoles in morphology but are developed in calcareous drifts. These soils, sometimes termed "grey wooded soils," were discussed by A. Leahey⁴⁰ and by H. C. Moss⁴¹, who preferred to assign them to a separate group. In this connexion, it is

of interest to note that H. M. Galloway¹² has reported an alkaline raw humus from Wisconsin, but as it lies directly on shattered limestone no podsol is observable.

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CHAPTER XI

CHERNOZEMS AND THEIR RELATED GROUPS

THE soils to be described in the present chapter are developed in semi-arid and arid climates with incomplete leaching, which results in the development of horizons of calcium carbonate deposition. They are developed under steppe or desert vegetation. The term *pedocal*, suggested by Marbut, may be conveniently used to cover the groups comprised in the succession from black earths to grey-brown and desert soils.

CHERNOZEMS* OR BLACK EARTHS

The study of the chernozems or black earths is of considerable interest and importance, not only on account of their wide extent and agricultural value, but because the modern study of soils in their natural relationships received its greatest impetus in the investigations and discussions of the problems of the origin of these and related soils. Further, regarding the diversity of the soils of the world as resulting from the varying intensity with which the pedogenic processes depending on temperature and moisture have operated, it is apparent that the black earths occupy, as it were, a central position between extremes with respect to the intensity of the factors that have affected their development.

The obvious feature of the black earths is, as the Russian name implies, their colour, which is due to the presence of humified organic matter. In the centre of the

*This spelling is used by the Commonwealth Bureau of Soil Science and by the U. S. Bureau of Soils, and I have therefore adopted it in place of "tserno-em," used in former editions.

chernozem area in Russia, where the conditions are most typical for the development of these soils, the colour is deep black, but as the adjoining soil provinces are approached, the black colour becomes less marked, changing into the grey of the degraded chernozems on the one side and the brown of the chestnut earths on the other.

The intensity of the dark colour produced would lead an observer familiar only with soils of humid climates to expect larger proportions of organic matter in the chernozems than actually occur. A sample of chernozem from the Ukraine, examined by the writer, contained only 3.2% of organic carbon, i.e., about 6% organic matter; yet the dark colour suggested a much higher proportion. As much as 16% of organic matter may be present in the central chernozems, but 8 to 10% is more usual. The dark colour may be attributed to some extent to the fact that these soils are base-saturated, and that the humification processes proceed in a neutral or even alkaline medium. It would seem, however, that other factors must be involved. Certain Lower Lias soils in Britain contain free calcium carbonate and notable proportions of organic matter, yet do not exhibit the dark colour of the chernozems. In all probability the high temperature to which these soils are subjected during summer, in conjunction with the high base-status, may determine their dark colour. It is noteworthy that, in many parts of the tropics and sub-tropics, dark coloured soils are associated with a high base-status, whilst base-unsaturated soils, under similar climatic conditions, show little or no humic colour, although they may actually contain higher proportions of organic matter than neighbouring dark coloured soils.

The thickness of the dark coloured layer in the chernozems varies considerably. The average for the best developed black earths is about 70 to 100 cm., with 40 cm. to 150 cm. as extremes. It is considered to be differentiated into two horizons, an upper, A_1 , and a lower, A_2 , the latter having a lighter colour and a lower organic content. The

thickness of the dark horizons and the organic matter content decrease towards the boundaries of the soil group. The sharpness of the transition to the underlying light-coloured parent material varies somewhat, but the change generally takes place within a few centimetres.

With regard to the inorganic profile, the typical chernozem shows complete leaching of soluble salts, incomplete leaching of calcium carbonate and calcium sulphate, and no leaching of silica or sesquioxides. Thus, whilst there is no accumulation of sodium salts in the profile, an unfailing mark of the chernozem is the zone of accumulation of calcium carbonate, sometimes accompanied by calcium sulphate. The absence of soluble salts in these soils of incomplete leaching may possibly be due to the fact that occasional abnormally wet seasons provide an excess of rainfall over evaporation, so that the profiles are completely leached. Such occasional leaching may be sufficient to remove any soluble salts that would otherwise accumulate in the profile.

The depth of this zone will vary according to the parent material. It approaches the surface more nearly the more calcareous is the parent material and also the more arid is the climate. The calcium carbonate zone may occur in the humic layer, but is generally near or below its lower limit. Above the main calcium carbonate layer, calcium carbonate occurs deposited in fibrous threads, like fungal hyphæ, and in small concretions which are sometimes hollow and may assume curious forms. Gypseous deposits may occur below the calcium carbonate horizon. In some cases, a second horizon of calcium carbonate accumulation may be observed at a depth of a few metres, but this would not appear to be a necessary characteristic.

A characteristic peculiarity of chernozems, and indeed of the adjacent chestnut coloured earths, is the presence of *krotowinas*. These are formed by the filling-in by calcium carbonate of the burrows of steppe animals.

The black earths are characterized by their well-developed granular crumb structure in the humic layer.

This is, of course, associated with their high base-status and the chernozem is thus the chief example of a "calcium soil." Although these soils may contain high proportions of clay, they offer few difficulties in tillage and consistently maintain their crumb structure.

So far as the clay complex of the soil is concerned, there would appear to be no vertical differentiation. It is unfortunate that no analyses of the clay fraction of Russian black earth profiles are available; but there is no evidence from field observations or from laboratory data to suggest the eluviation of sesquioxides or silicic acid. Neither is there any evidence of the eluviation of the clay complex as such, with consequent development of a texture profile. It is held by A. Stebutt¹ that, in the chernozems, the conditions for the formation and maintenance of the aluminosilicic weathering complex are at optimum. Increase of temperature and increase in humidity both favour the destructive processes whereby the component silicic acid and sesquioxides are liberated and, in the podzols, differentiated.

The brown or reddish-brown colours associated with the presence of free sesquioxides are entirely lacking in the typical chernozem profile, in which the mineral colour is predominantly brownish-grey. The transition to degraded chernozems in the direction of increased humidity is marked by the appearance of brown sub-soil horizons. The transition to higher temperature conditions is marked also by the development of reddish-brown colours throughout the profile, indicating the destruction of the weathering complex without eluviation.

In Russia, the black earth region is characterized by cold winters and hot summers, with a moderate rainfall. Data presented by P. Kossowitsch² show mean January temperatures from -20.8°C in Siberia to -3.5°C in the Ukraine, and mean July temperatures varying from 16.7°C in Siberia to 23.3°C in S. Russia. The mean annual rainfall varies from 300 mm. to over 500 mm. A considerable proportion of the precipitation is in the form of snow, and the

summer rainfall is heavily outweighed by evaporation. These conditions result in steppe vegetation which grows luxuriantly in spring and in early summer. The ensuing drought puts an end not only to active plant growth but also to micro-biological activity in the soil.

C. C. Nikiforoff³ has discussed the general problem of chernozem formation. Concerning humification, he points out that each season's growth is returned as residues under natural conditions. The mat of dead vegetation of each year begins to decompose in the following spring and the process extends over succeeding years, so that each cycle overlaps phases of preceding cycles. This author considers that the pedological origin of the calcium carbonate accumulation has not been definitely proved. Most chernozems have in fact been developed from lime-rich parent materials.

In Russia and Asia, where the black earths have been principally studied, the parent material is generally loess and the textural range is limited by the character of this deposit. The extent of the loess and of the chernozems are, however, not necessarily identical, for not only do other soil groups occur on the loess, but chernozems may also be developed from other parent materials.

K. D. Glinka⁴ describes the following profile from Kogalnitza, Rostov:—

- A₁. 0-20 cm. Black with brownish-grey shading, breaking down into irregular lumps and eventually into a porous fine grained material. Effervescence with HCl from 8 cm.
- A₁. 20-55 cm. Greyish-black granular; more cohesive below. Columnar and nut structure.
- A₂. 55-90 cm. Gradual transition to greyish-brown mottled appearance. Nut structure. Krotowinas. Structural elements with white coating of carbonate.
- A₂. 90-105 cm. Disappearance of dark colour and irregular transition to brownish-yellow clay. Krotowinas. Calcium carbonate concretions.
- A₂-C. 105-185 cm. Yellowish-brown clay with vertical tongues of humous material. Calcium carbonate concretions.
- A₂-C. 185-240 cm. Humous streaks in wet pores. Decrease in carbonate concretions.
- C. Yellowish-brown clay.

Germany. Soils which appear to belong to the black earths occur in many parts of Germany. The following profile is described by K. Von See⁵, from near Magdeburg :—

- A. 0-55 cm. Humous carbonate-free loess. Loose and porous. Below the root horizon down to 30 cm. a greyish-brown horizon with lump structure over an almost black humous layer with tendency to polyhedral structure. Occasional flecks of greyish-yellow carbonate-free loess. At the transition to parent loess a zone rich in carbonate.
- C. Yellow or yellowish-grey unstratified loess.

V. Hohenstein⁶ describes numerous chernozem profiles developed on boulder marls, clay marls, and glacial sands, in Eastern Germany. They are characterized by the leaching of carbonate from the upper horizons down to 20-100 cm. and the development of a zone of carbonate accumulation. The humus content, 2-4%, is rather less than in the Russian black earth region. The prevailing colours are coffee-brown to dark brown. They are considered to have been formed under an earlier steppe climate.

W. Laatsch⁷ has discussed the distribution and development of soils of the chernozem type developed on loess in the vicinity of Halle. It appears that the conditions in this region represent the limit of stability for such soils, for there is a tendency towards degradation and the production of brown forest soils. Where the mean annual rainfall is greater than 500 mm. the brown forest soils are developed on loess without an intermediate chernozem stage.

Czechoslovakia. V. Novák⁸ describes "Hanna" soils in Czechoslovakia which appear to belong to the chernozem group. A typical profile from Hulin showed :—

- 0-40 cm. Dark loam with brownish tinge. Loose crumb structure sharply delimited below.
- 40-70 cm. Compact humous loam easily breaking down into crumbs.
- 70-100 cm. Dark compact loam.
- 100-150 cm. Yellowish loam.
- 150-350 cm. Light coloured loam with concretions and superficial deposits of calcium carbonate.

The mechanical texture is very uniform. The humus content decreases gradually from 4.83% in the surface horizon to 3.67% at 100 cm. There is then a sharp fall to 2.00% at 120-140 cm.

Another type of Hanna soil differs from that described above in being lighter in colour and poorer in humus. Calcium carbonate concretions appear at 130-140 cm.

North America. Chernozems occur over considerable areas of North America in the States or Provinces of Saskatchewan, Alberta, Minnesota, the Dakotas, Nebraska, Kansas, Colorado, Oklahoma and Texas. Whilst the northern soils resemble the Russian chernozem, some change in character occurs in passing to the warmer conditions of lower latitudes.

A northern chernozem from N. Dakota, mapped as the Barnes series (see Plate VI), is thus described by C. F. Marbut⁹ :—

- I. 0-12 in. Heavy black loam. Irregular clod structure in top 4 in., ill-defined columnar structure below.
- II. 12-22 in. Dark greyish-brown clay loam with ill-defined columnar structure. No effervescence with acid.
- III. 22-32 in. Light greyish-yellow to greyish-brown, heavy silt loam or silty clay loam. White spots and splotches of calcium carbonate. Columnar structure disappears in this horizon, which is marked by maximum of carbonate accumulation.
- IV. 32-40 in. Mottled silty clay loam. Small iron oxide stains and concretions present. Spots and concretions of calcium carbonate less abundant than in III.
- V. Greyish-brown silty clay loam with iron oxide stains and concretions. Calcium carbonate present in disseminated form. This is the parent glacial drift from which the profile is developed.

The following is Marbut's description of a southern chernozem from Texas, mapped as the Amarillo series :—

- I. Yellowish laminated fine sandy to silty loam becoming darker coloured downwards. Presence of æolian material in surface. Grass roots abundant below. Thickness about 4 in.



[Photo, U.S. Dep. Agric. Soil Survey Division
CHERNOZEM PROFILE, CASS COUNTY, N. DAKOTA, U.S.A.]

- II. Dark brown to very dark brown, generally clay loam. Dark yellowish-brown or reddish-yellow on being crushed. Granular structure becoming coarser with depth. Thickness about 12 in.
- III. Reddish-yellow clay loam, still with darker coloured coatings in structural elements. General tendency to columnar structure.
- IV. Reddish-yellow material with much calcium carbonate. Similar structure to III.
- V. Parent material; unconsolidated calcareous silt and clay.

Data from M. S. Anderson and H. G. Byers¹⁰ for a Texas profile, which, though somewhat different from the Russian chernozem, is essentially similar in its general type of development, are given in Table XXXI. The soil series is the same as that described above.

TABLE XXXI.—COMPOSITION OF COLLOIDAL MATERIAL OF A PROFILE FROM THE AMARILLO SERIES

Depth	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SiO ₂ /R ₂ O ₃
0-5 ins. ...	50.51	22.04	8.80	3.10
10-20 ins. ...	51.51	22.71	8.61	3.09
30-40 ins. ...	51.32	22.43	8.46	3.13
54-64 ins. ...	51.23	24.08	8.19	2.97
70-75 ins. ...	38.42	17.64	5.71	3.06 (CaCO ₃ horizon)
96-100 ins.	45.88	20.09	6.89	3.18

The composition of the clay colloid shows a remarkable constancy throughout the profile and there is no evidence for eluviation either of silicic acid or sesquioxides.

H. W. Hawker¹¹ describes a range of soils in the Rio Grande valley of Texas which show successive stages of leaching from young delta soils to mature terrace soils with calcium carbonate accumulations at 4 to 8 feet. The mean annual rainfall is 22.5 inches and the profile consists of light brownish-grey to greyish-brown soil overlying heavy bluish-grey clay, mottled yellow and, sometimes, red. The surface horizons are non-calcareous.

India. There is in India a well known type of soil known as the *regur*, or *black cotton soil*, which occupies a large area in the southern half of the Peninsula. The natural vegetation appears to be of a grass steppe type. Regur is usually of a clay character and varies in depth from 1 to 2 metres, occasionally reaching 5 metres. On drying it shrinks and cracks to such an extent that it is often said that "black soil ploughs itself." Like the chernozem, it is characterized by a zone of calcium carbonate concretions ("kunkur"). The parent material is generally a black basalt trap, the so-called Deccan trap. The organic matter content is generally low and the black colour, according to H. E. Annett¹², is due in part to the presence of finely divided titaniferous magnetite.*

A. D. Desai¹³ has described black cotton soils of the Hyderabad-Deccan state in India. These soils are generally heavier in texture than the adjacent red soils. They are derived from the Deccan trap and gneissic complex. The depth and development of the calcium carbonate horizon varies considerably and may be as much as 8 to 10 feet and, in exceptional cases, 30 to 40 feet.

The climatic conditions for the Indian regur soils differ from those in the Russian chernozem region in that the temperature, even in the winter months, is always considerably higher. The rainfall, rather more abundant than in the Russian black earth region, is, however, insufficient to compensate for the great evaporation resulting from the high temperatures which prevail, and incomplete leaching results. The climate is thus not identical with that of the Russian chernozem region. Regur might, therefore, be described as tropical black earth. Black soils occur in Morocco, Kenya, and other parts of Africa, which may have affinities with the black earths, and are, probably from their resemblance to regur, also termed "cotton soils."

*W. H. Harrison and M. R. R. Sivan (Mem. Dept. Agr. Ind. Chem. Series, 1912. II. No. 5) only admit Annett's explanation for the trap areas. Elsewhere, colloidal iron and aluminium silicates are held responsible for the black colour.

Argentina. The soils of the Argentine Pampas would appear also to present many similarities with the black earths and further work may result in their being assigned to this group.

The black earth represents the soil type developed under the conditions which prevail on the arid side of the boundary between humid and arid soils. When they have been completely investigated in all parts of the world where they occur, it will probably be possible, as Marbut suggests, to divide them into sub-groups on the basis of the prevailing temperatures. We may thus speak of high latitude, mid-latitude, sub-tropical, and tropical chernozems. The common characteristics are a dark A horizon, relatively rich in base-saturated organic matter, a high base-status, and the presence of an horizon of calcium carbonate accumulation. The vegetation is a closed association of steppe, savannah, or pampas character, either devoid of trees or else with isolated individuals as in the S. African bush-veldt.

BLACK COTTON SOILS OF KENYA

Grey and black soils occur in Kenya which may represent tropical chernozems. D. S. Gracie¹⁴ describes a group of soils, locally termed "black cotton soils," which appear to exhibit various stages of degradation. In the undegraded type, the profile consists of a black clay, rich in exchangeable calcium, overlying a layer of calcium carbonate accumulation. In the degraded soil, there is a grey layer at the surface with acid reaction and low exchangeable calcium content. This overlies the black clay. A still further stage of degradation is seen in certain soils with acid greyish-brown surface horizons. Degradation appears to involve a loss of organic matter. Black cotton soils may also be developed on lighter textured parent materials. They may be analogous with the "vlei" soils (see p. 283) of the humid regions of Kenya, and tend to occur in plains and depressions in relatively hot and dry regions. Their complete

analogy with the chernozems of higher latitudes would appear to be still unproven.

H. H. Bennett and R. V. Allison¹⁵ report soils with zones of calcium carbonate accumulation in the drier parts of Cuba, but doubt their analogy with the chernozems of the United States.

CHESTNUT-COLOURED SOILS

The group known as the *chestnut-coloured soils* (also called *chestnut earths*) occurs in Russia and Asia on the arid side of the region of the related chernozems. They differ from chernozems principally in the lower proportions of organic matter in the humous layer and in the closer approach to the surface of the zone of carbonate accumulation. Both circumstances are intelligible consequences of the drier character of the climate as compared with that of the chernozem zone.

According to K. D. Glinka¹⁶, the A_1 horizon consists of an upper portion (5-7 cm.) of light colour and loose stratified structure, and a lower portion of smaller thickness and compact structure, lacking the characteristic granular character of the chernozems. The A_2 horizon, which may reach 60 cm. in thickness, is lighter in colour and compact. Both horizons show a prismatic structure by reason of the occurrence of vertical cracks. The organic matter content of the humous horizons varies from 3 to 5%. The mechanical composition is fairly uniform and there is probably no vertical differentiation of the constituents of the clay complex. Accumulation of calcium carbonate may occur in the A_1 horizon or even near the surface. Gypsum may occur in the lower part of the A_2 horizon.

The colours of the humous horizons are greyish-brown and do not appear to be influenced by the presence of free hydrated ferric oxide.

The natural vegetation of the chestnut earths is low-grass steppe.

BROWN AND GREY SOILS OF THE SEMI-DESERT

With passage to more arid conditions, the chestnut-coloured soils are replaced successively by *brown* and *grey semi-desert soils*. These differ from the chestnut coloured soils by their lower content of organic matter and by the closer approach to the surface of the calcareous and gypseous horizons. The grey soils are sometimes called *sierozem*.

United States. In a study of soil zones in northern Wyoming, J. Thorp¹⁷ has been able to trace a complete succession from grey-brown desert soils to podsoles in passing from the arid plains to the relatively humid mountain regions. The grey-brown desert soils, developed under mean annual rainfalls of 5-10 inches, show the following profile characters :—

- A₁. 0-1 in. Pale grey-brown "crust and mulch" with fine vesicular structure in dry condition.
- A₂. 1-6 in. Light greyish to yellowish-brown slightly laminated soil of medium texture.
- B₁. 6-9 in. Compact cloddy, yellowish-brown soil of slightly heavier texture than above horizon. Most compact horizon in profile.
- B₂. 9-(18-40) in. Horizon of calcium carbonate accumulation of varying thickness. Calcium carbonate decreasing in lower part of horizon. White or pinkish gypsum often interspersed with upper layers of parent material below carbonate horizon.
- Below 18-40 in. Parent material. Rounded gravels of various rocks. Pebbles coated with indurated calcium carbonate.

A distinct columnar structure is seen in the lower A and B horizons. Calcium carbonate is present up to the surface. In slight depressions the accumulation of calcium carbonate and gypsum becomes more pronounced.

The vegetative cover is scanty and consists mainly of sage brush, *Artemisia tridentata* and salt sage, *Eurotia lanata*.

In many parts of the arid regions of the Western United States, the calcium carbonate horizon attains a considerable degree of induration. Under the local name of "caliche," it is frequently used as a surface for roads.

Owing to the incompleteness of leaching in soils of the pedocal class, there is a general tendency for sodium salts to occur in the profile. This is more pronounced in the more arid regions. Where, owing to topography, a ground-water level occurs near the surface, saline or alkaline soils may occur. Such soils may be considered to be analogous to the meadow and peat soils of more humid regions.

Sudan. The cotton soils of the Eastern Gezira in Sudan appear to be grey-brown semi-desert soils of the pedocal class. They are developed from wind-borne material of rather heavy texture. The rainfall is about 400 mm. per annum, of which about two-thirds falls in July and August. The natural vegetation is sparse thorn scrub.

A typical profile, described by H. Greene¹⁸, shows a surface soil of rather dark brown colour down to 2 feet. Below this is a grey layer which is penetrated by tongues of the top brown soil. In the upper part of the grey layer, ill-defined, detached lumps of grey soil occur surrounded by brown soil. Those nearer the surface contain small specks of calcium carbonate, whilst those lower down contain gypsum. At the lower limit of the grey layer, about four feet, white crumbly aggregates of calcium carbonate occur, amounting, at their greatest concentration, to 3% of the soil. Below this zone are crystals of gypsum in a matrix of yellow-brown soil.

The drying-out which occurs in the dry months of the year leads to the development of numerous cracks which extend for a considerable depth into the subsoil. These are filled with loose material blown from the surface by wind, and there is, in this way, a certain amount of circulation within the profile.

The organic matter content is low—generally below 1%, even in the dark-brown surface soil. In addition to gypsum, sodium salts are present and are closely correlated in amount with the gypsum content.

DESERT SOILS

These form a rather ill-defined group of soils which have not yet been sufficiently studied in detail. It is generally considered that weathering in the desert is mainly physical, but it must be remembered that even in desert regions rain does fall occasionally and that the subsurface layers may be from time to time sufficiently moistened for hydrolytic decomposition of silicates to take place. Further, intermittent flooding from adjacent upland regions may provide seasonal moisture. Such intermittent supplies of moisture would not affect the actual surface horizons to any great extent, and here the weathering remains substantially physical in character.

It is somewhat surprising that in desert regions evidences of water action are often very spectacular. Although the rainfall is low, it is often intense and with the absence of vegetative cover flood water soon gathers, particularly when streams are fed from wetter mountain regions. And thus in the broad desert valleys extensive alluvial fans and spreads of gravel are common.

Vegetation is absent except for isolated desert shrubs and small trees, such as the cacti and sagebrush of the western American deserts. Such soil development as occurs is unaffected by the processes of humus formation and desert soils are practically humus-free. Wind erosion is very marked, and a common phenomenon is the so-called "desert pavement," consisting of coarse stones or rock fragments from which the originally accompanying fine material has been blown away. Beneath the desert pavement which acts as a protection, fine material is found. The surface of the stones and rocks of the pavement is often covered with a thin brownish film, known as desert-varnish.

C. C. Nikiforoff¹⁹ has studied the pans and crusts that are characteristic of the sub-surface horizons of desert soils particularly in Nevada and southern California. A distinction is drawn between crusts and pans. Crusts are considered to be formed by deposition from ascending solutions during

periods of desiccation. The cementing materials are most commonly calcium carbonate or gypsum, but ferruginous crusts may also occur. Such crusts should not, according to Nikiforoff, be confused with the calcium carbonate horizons deposited in pedocalic soils under higher rainfall and under the influence of a cover of steppe vegetation. Pans, which consist of an accumulation of clay and fine material, are considered to be the result of hydrolytic decomposition of minerals in the intermittently moist sub-surface horizons.

I. C. Brown and M. Drosdoff²¹ describe a profile from the gentle lower slope of a low granitic hill in the Mojave desert. It shows two inches of loose gritty greyish-brown loam, underlain by a reddish-brown gritty clay, which extends down to about fourteen inches, where it grades into the weathered granitic rock traversed by seams of calcium carbonate. On an alluvial fan the surface twelve inches was light brownish-grey structureless gritty sand, underlain by about eighteen inches of reddish brown gritty clay loam with prismatic structure, grading into weakly lime-cemented gritty sand. At three feet there was a sharp change to friable gritty brown sand of granitic origin. The analytical results support Nikiforoff's view that the clay horizon is of hydrolytic and not of illuvial origin.

California. In the desert soils of southern California, developed in colluvial fans of material of igneous origin, well-marked pans are found. The degree of development of the pan is made by C. F. Shaw²⁰ the basis of the separation of these soils into series. In the mature San Joaquin series, the profile consists of reddish-brown heavy textured soils passing through brown or reddish-brown subsoils to brown or red "iron" hardpan at 40-90 cm., with more or less calcium carbonate, overlying brown pervious unweathered material.

The profiles of San Joaquin and related soils show abundant evidence of chemical weathering, whose occurrence, in a region of scanty rainfall, may be due to natural

irrigation by flood and seepage water from the adjacent mountains.

S. Africa. Red and brown soils with calcium carbonate and ferruginous pans are found in the semi-desert Karroo of South Africa.

POSITION OF EQUATORIAL PEDOCALS

Pedocalic soils extend over a wide range, being bounded in the north by sub-arctic tundra and extending into equatorial regions. Certain workers have distinguished northern, mid-latitude and tropical pedocals. F. E. Kenchington²² makes an interesting suggestion for distinguishing two great groups of chernozem-like soils. On either side of the equatorial humid belt there is a desert belt of varying width. To the north of this belt, in the northern hemisphere, the zone of transition to the temperate humid regions is occupied by the classical chernozems and their congeners. To the south, in the zone of transition to the equatorial humid belt, occur a group of pedocalic soils for which the Sudanese term *teen-suda* is proposed. A similar distribution is envisaged for the southern hemisphere. Kenchington would regard the regur soils of India and the pedocalic soils of the Sudan and surrounding regions as belonging to the *teen-suda* group. In the writer's opinion this suggestion is a valuable contribution to the study of the pedocals and merits careful examination.

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CHAPTER XII

HYDROMORPHIC SOILS AND PEATS

THE term hydromorphic (or hydromorphous) proposed by S. S. Neustreue is a convenient name for all those soils in which profile development is dominated by the effect of sluggish or impeded drainage. Since the presence of excessive moisture implies diminished aeration, it might be permissible to describe these soils as soils of anaerobic metabolism in contradistinction to soils of free aeration, described by H. Del Villar² as soils of free aerobic metabolism (*suelos de metabolismo libre en medio aereo*). In the strict sense of the term we should include with hydromorphic soils those soils in which sodium salts are present or have affected an earlier stage of development. Such soils, however, are more conveniently discussed separately and are, therefore, not included in the present chapter.

The excessive wetness in the profile may arise in two distinct ways. On the one hand, it may be due to the presence of a regional water-table sufficiently near the surface to affect profile development, i.e., when the soil horizons are in the so-called "capillary fringe" or the wetness may be a consequence of the impervious character of the soil material, more particularly in the sub-soil horizons. The impervious character may be inherited from the parent material, as in heavy clay soils, or it may be the consequence of the development of an impervious horizon by pedogenesis as in planosols and gley podsols.

The degree of wetness will be governed to a large extent by the climate. In a wet climate, such as Wales, soils showing impeded drainage are much more frequent than in a drier climate, because there is so much more moisture to dis-

pose of. In some climates the wetness may be seasonal as in many tropical soils that are swamps in the rains, but almost completely dry in the dry seasons.

In any given region the distinction between soils of free and soils of impeded drainage is of the greatest importance both for its significance in profile development and for its bearing on the actual behaviour of the soil under agriculture or forestry. Many writers, following N. M. Sibertzev³, regard these soils as *intrazonal*, implying that they are in a sense of accidental or local occurrence among the great world groups. Yet, in view of their wide extent, it would appear better to regard them as one of the major soil categories.

TUNDRA

These soils occur in sub-arctic regions such as Northern Europe and Asia, and Northern Canada. They lie outside the limits of forest and are occupied by mosses, carices, dwarf willows, festucas, etc. In the tundra region, the dominant factors in soil formation are physical weathering and waterlogging. The latter is occasioned by the scanty evaporation, which results in the prevalence of a humid climate even where the rainfall is comparatively small. Chemical weathering and micro-biological activity are naturally less pronounced than in warmer climates, but are not entirely suppressed. These soils are commonly assigned to the podsollic group, but the prevalence of waterlogging among the conditions of their development suggests that they would be more appropriately grouped with the ground-water soils.

The characteristic feature of the tundra profile is the occurrence, below a certain depth, of a perpetually frozen layer, whose presence is, in some districts, not inconsistent with a fair level of fertility during the growing season.

A typical tundra profile has been described by Ssukatschev¹. The succession is as follows:—

1. Humous grey-brown horizon. Thickness about 3 cm., containing occasional undecomposed plant remains.

- II. Yellowish-grey horizon; occasionally greyish-brown, ochreous friable loam. Thickness 3-5 cm.
- III. Greyish-blue uniform sticky loam of semi-fluid consistency. Thickness 8-10 cm.
- IV. Brownish-yellow loam similar to horizon II., but more compact. Thickness 2-3 cm.
- V. A compact brownish-grey solid loamy horizon, often showing at 40-60 cm. dark fluid mottlings apparently of a humous character. Frozen below 79 cm. from surface, but retaining the same character for a further 10 cm.—the limit of exploration.

The bluish-grey horizon is apparently the characteristic mark of tundra, becoming thicker with increase and thinner with decrease of moisture. In sandy profiles, it disappears, presumably owing to better aeration.

When the surface of tundra becomes frozen, the semi-fluid greyish-blue horizon is held under pressure, owing to the expansion of water below 4°C, and this leads, in some cases to an eruption through the thin frozen layer, in other cases, to the surface becoming thrown into hummocks. The eruption of material leads to a mixing of the profile and tends to obliteration of horizons.

Tundra soils result mainly from physical weathering and are consequently poor in clay. They exhibit a natural tendency to peat formation. The peat horizon is often dissected by running water into a characteristic hummocky formation.

The occurrence of a perpetually frozen subsoil in the tundra region has been discussed by C. G. Nikiforoff⁵. Whilst the prevalence of a mean annual temperature below freezing point might sufficiently account for the existence of a permanently frozen layer, it has been held by some investigators that this phenomenon is a survival from the Glacial Period. Perpetually frozen subsoils occur outside the tundra region and may sometimes underlie the more northern podsols, black earths, and chestnut earths. R. R. McKibbin⁶ records such an occurrence in northern Manitoba.

MEADOW OR GLEY SOILS AND THEIR RELATED TYPES

The soils described under this heading are termed "Wiesenböden" and "Gleyböden" by continental writers. In the absence of a more suitable term, the name *meadow soil* or *gley soil* is used to describe mineral soils whose profile characters are dominated by the occurrence of a high water-table or an impervious layer or layers, impeding percolation.

These soils, which have certain affinities with the pod-sols and occur under similar climatic conditions, owe their distinctive characters to lack of aeration through the presence of a high water-table or the restriction of drainage by an impervious layer. The simplest case is that in which a water-table occurs in a soil developed in material permitting free percolation. Here the water-table fluctuates according to the general balance of rainfall and evaporation, being highest in winter and lowest in summer. There are thus three zones in the profile, namely, (1) a surface zone sometimes of negligible depth in which conditions are generally aerobic; (2) the next zone marked by the limits of fluctuation of the water-table in which aerobic and anaerobic conditions alternate; and (3) a zone below the lowest level of the water-table in which conditions are permanently anaerobic and therefore reducing.

The surface horizon in which most of the root development of the natural vegetation takes place is generally dark grey or brownish-grey with a fairly high organic matter content. The greyness may be due to a lateral leaching of iron, for the seepage water in ditches frequently shows deposits of hydrated ferric oxide (ochre). Rusty markings can often be seen along root channels in this horizon.

The second horizon is lighter in colour because of its lower organic matter status, and there is often a sharp transition marking the limitation of root development and humus addition imposed by the proximity of the water-table. The ground colour is grey but there are also rusty streaks, mottlings, or even concretions, resulting from the oxidation

during the aerobic stage of soluble ferrous compounds formed during the anaerobic stage. The decomposition of hydrated ferric oxide in this horizon may attain considerable proportions giving rise to "lake ore" or "bog iron-ore." Under similar conditions in the tropics lateritic horizons are developed (cf. pp. 412 *et seq.*). Other secondary depositions may occur in this horizon including manganese dioxide, gypsum, and calcium carbonate. There may also be an enrichment in clay, not necessarily through eluviation, but as a consequence of hydrolytic decomposition.

Another morphological feature of this horizon is the development of a characteristic greyish film or coating on the surface of the structural elements, which often tend to be prismatic or coarsely polyhedral. This appearance, known as "gleying," is very characteristic, and the horizon is known as the *gley* or *glei* horizon. Whilst the rusty mottling generally accompanies gleying, it is not invariably present, and incipient gleying can be seen, particularly in sandy soils without observable rust mottling.

In the permanently anaerobic horizon below the lowest level of the water-table, there is no root penetration and the organic matter content is very low. Owing to the prevalence of reducing conditions, the material has a bluish-grey, bluish-black, or greenish-grey colour due to the presence of ferrous compounds, among which ferrous sulphide, FeS , and vivianite, $\text{Fe}_3(\text{PO}_4)_2$, may be present.

In soils where wetness is due to the impervious character of the profile material, the three zones are less clearly defined. In many cases, as for example in certain heavy clay soils, the wetness is confined to the top few feet which overlie a compact dry mass of clay into which moisture does not penetrate. In such soils, the profile may become almost completely dried out in the summer and the zone of permanently reducing conditions is absent. The zone of gleying and rust mottling may also be more diffuse.

Very great variations may occur in the character and thickness of the humus layer and in the development of

mottling and gleying in the gley horizon through the deposition of materials from the ground water. The general grey-ness of the soil horizons, the development of prismatic or polyhedral structure, the occurrence of gleying, and the presence of secondary deposits are all indications of this soil group.

The natural vegetation of meadow soils is generally of a gramineous, juncaceous, or caricaceous type. They occur also under wet woodland vegetation, as in the so-called *taiga* of Siberia. When the ground-water level approaches more nearly to the surface and permanently wet conditions prevail, the tendency is towards peat formation with the development of a gley podsol or peat podsol profile, consisting typically of up to 1 foot of peat underlain by grey mottled subsoil. This type passes into the peat soils.

Gley soils are common in depressions and hollows in regions of podsollic soils. In passing from an upland to the bottom of a depression in such regions, a regular succession of profiles can frequently be observed. In the upland, with free drainage and scanty accumulation of peaty organic matter, iron podsoles may occur. In the moister lower levels, the humic layer becomes thicker, and gley podsoles and peat podsoles result. In still lower ground, the water-table is sufficiently near the surface to give the gley horizon characteristic of a meadow profile, which gives place in turn to a peat profile. Gley podsoles may result through impedance consequent on the development of ortstein in podsol profiles.

Gley soils are essentially local in character and depend, in the main, on topographical conditions which influence the movement of underground water. Most typically they are developed in hollows, but where drainage is impeded by impervious strata on slopes, the typical characters of the gley profile may also be developed.

Gley soils occur throughout middle, northern, and western Europe, and, indeed, throughout all the humid regions. In Europe, they attain their greatest development in the Pripet marsh region of Poland.

Analogous conditions in more arid regions may give rise to saline and alkaline soils. There are also characteristic soils associated with high ground-water in the tropics. These will be considered at a later point.

Finland. B. Frosterus⁷ gives the following description of a gley soil in Finland:—

- A₁. 0-23 cm. Brownish-grey sandy peat.
- A₂. 23-27 cm. Greyish sandy clay.
- A₃. 27-32 cm. Yellowish-brown plastic clay passing sharply into
- B. 32-45 cm. Ochreous plastic clay passing gradually into
- B-G. 45-120 cm. Grey clay with abundant rusty threads and concretions arranged in three horizontal layers at 45, 50, and 80 cm., respectively.
- G₁. (Gley horizon). 120-175 cm. Grey clay with scattered rusty threads and prismatic structure.
- G₂. 175-195 cm. Prismatic clay with superficial rusty coating on the individual columns into which the horizon is dissociated by vertical cracks.
- CG. Blue clay, occasionally inky black containing vivianite.

Germany. The soils known in parts of Germany as "Molkenböden" may be grouped with the meadow soils. K. V. Von Falckenstein⁸ describes soils of this kind developed from the middle Bunter sandstone under conditions of impeded drainage in the Weser valley. The following profile is typical:—

- 0-3 cm. Litter layer.
- 3-16 cm. Bleached humous layer.
- 16-50 cm. Compact layer with yellow streaks becoming more stony below.

Analyses of the successive layers show marked differences from podsoles, for there is no leaching of alkalis and alumina and only a slight downward movement of ferric oxide. The bleaching in the surface horizon is considered to be the effect of reduction of ferric to ferrous compounds.

Scotland. W. G. Ogg⁹ describes a gley soil developed on Silurian shale boulder clay in the Moorfoot Hills. The altitude is 1,250 feet, the mean annual rainfall 35-40 in., and the vegetation *Juncus communis* and *Carex Goodenovii*

dominant, with *Holcus lanatus*, *Trifolium repens*, and *Anthoxanthum odoratum* abundant.

- (1) 0-5 cm. Mat of roots and moss.
- (2) 5-15 cm. Brownish-grey silty loam; wet; no definite structure; few stones; roots common; some brown patches along root-channels.
- (3) 15-22 cm. (Variable.) Grey silty loam with brown patches and streaks; wet; few stones; roots common; brown staining along root-channels.
- (4) 22-35 cm. Brown silty loam with greyish tinge; wet; slightly gritty; few stones; much brown mottling and staining along root-channels.
- (5) 35-55 cm. Greyish-brown silty loam with sandy patches; wet; stones common; blackish particles or concretions; roots penetrate; brown staining along root-channels.
- (6) 55 cm.+ Stony silty loam; grey-brown with brown patches; very wet; gritty.

The principal analytical data are given in Table XXXII.

TABLE XXXII.—ANALYTICAL DATA FOR SCOTTISH GLEY SOIL

Depth (in cm.)		0-5	5-15	15-22	22-35	35-55	55 -
pH	...	5.2	5.3	5.6	5.4	5.8	5.5
Ignition loss	...	18.4	12.6	7.3	5.2	4.1	3.6
Clay	SiO ₂ /Al ₂ O ₃	2.96	2.85	2.98	2.89	2.79	2.29
	SiO ₂ /R ₂ O	2.44	2.32	2.37	2.28	2.12	1.82
	Al ₂ O ₃ /Fe ₂ O ₃	4.69	4.38	3.89	3.74	2.41	3.87

Wales. Soils developed under conditions of impeded drainage are commonly encountered throughout Wales, but occur more frequently in districts of high rainfall.

We may distinguish two types, namely, soils in which the impedance of drainage is due to the high level of the water table, and soils in which impedance is due to the occurrence of a relatively impervious stratum in the subsoil.

As an example of the first type, a profile from near Bangor, N. Wales, may be described. The parent material

is alluvium derived from Ordovician Shale. The soil is described for soil survey purposes as the Conway series.

The profile is as follows :—

Depth	Description	Clay %	Organic Carbon %	pH
0-8 in.	Grey heavy loam	28.9	5.30	6.1
8-20 in.	Grey mottled-brown clay	35.7	2.47	5.8
>20 in.	Grey mottled-brown heavy clay	45.9	1.06	5.7

The composition of the clay fraction in the successive horizons is as follows :—

Horizon	$\text{SiO}_2/\text{Al}_2\text{O}_3$	$\text{SiO}_2/\text{R}_2\text{O}_3$	$\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$
0-8 in.	2.70	2.40	8.00
8-20 in.	2.73	2.43	8.01
>20 in.	2.62	2.26	6.28

This soil is typical of considerable areas of wet lowland soils in Wales. The vegetation is generally grass and rushes, together with miscellaneous water-loving plants in the wetter situations. All stages of transition to lowland peat soils may be observed.

The data for the composition of the clay fraction are instructive. In spite of the occurrence of much brown mottling in the lower horizons, there does not appear to be any considerable eluviation of ferric oxide. The low figures for this constituent throughout the profile are reminiscent of the A horizon material of a podsol profile and it may be that the whole profile consists of A horizon material removed by former erosion and deposited in its present low-lying situation.

The iron content of the clay of bottom soils is not always so low as in the profile described, and the grey colour may be partly attributed to the existence of iron in the ferrous state consequent on the reducing conditions which commonly obtain in such soils.

An example of a soil with drainage impeded by an impervious stratum is furnished by a profile from Llanfairpwll, Anglesey, mapped under the name of the Gesail series for survey purposes. It occurs under grass vegetation. The

parent material is micaceous schist boulder clay and the profile is as follows :—

Depth	Description	Clay %	Organic Carbon %	pH
0-10 in.	Greyish loam	20.7	3.6	6.9
10-20 in.	Greyish mottled micaceous loam	15.7	0.8	8.0
20-30 in.	Grey and brown mottled micaceous heavy loam	14.3	1.4	8.0

A certain amount of manganese dioxide occurs in the lower horizons, and the pH values determined by the quinhydrone method are rather too high.

The composition of the clay fraction in the successive horizons is as follows :—

Horizon	SiO ₂ /Al ₂ O ₃	SiO ₂ /R ₂ O ₃	Al ₂ O ₃ /Fe ₂ O ₃
0-10 in.	2.50	2.05	4.53
10-20 in.	2.63	1.99	3.11
20-30 in.	2.66	2.02	3.15

There is a certain eluviation of ferric oxide, but there is no very decided difference between the composition of the clay fraction in the different horizons.

In the two profiles described above, the mottled sub-surface horizons may be equated with the gley horizons of continental writers. It should be noted that the brown or reddish-brown appearance is not due to a deposition throughout the mass of the soil as in the B horizon of podsol profiles, but rather to superficial deposition on the structural elements. This is reflected in the comparatively slight enrichment in ferric oxide shown by the analytical figures for the clay fraction.

One feature of meadow soil profiles is the fairly sharp decrease in organic matter content in passing from the turf layer. The moisture conditions are such as to restrict root development to the surface, so that comparatively little organic matter is present in the layers subjected to water-logging.

England. Certain of the soils of central and eastern England derived from heavy clay formations might be

appropriately grouped with the meadow soils. The following profile at Lolworth, Cambridgeshire, on Kimmeridge Clay is described by F. Hanley¹⁰:—

- 0-9 in. Dark brown clay loam with flints: mottlings.
- 9-21 in. Grey-brown clay with light brown mottlings.
- 21-40 in. Lead-grey clay with brown mottlings.
- >40 in. Lead-grey clay; yellow seams in upper portion and pockets of crystalline gypsum.

The analytical figures show an almost complete leaching of carbonates and a marked accumulation of gypsum below 40 inches. The soil contains 32.8% clay, but the lower horizons have from 60-70% clay.

United States. Gley soils are of common occurrence throughout the Union and a perusal of the publications of the Soil Survey will afford many instances. A typical example is the Elkton series found in many parts of Maryland and the adjoining states. These soils occur in flat areas or small depressions and near the heads of streams and are derived from unconsolidated clay sediments. A description by S. O. Perkins and H. B. Winant¹¹ of a profile near Stevensville, Md., is as follows:—

- A. 0-5 in. Light grey silt loam, compact when dry but friable under favourable moisture conditions. Floury feel.
- B₁. 5-6 in. Light grey heavy silt loam, faintly mottled with rust-brown.
- B₂. 8-40 in. Light grey silty clay, mottled rust-brown. Slightly plastic with thin layers of grey fine sand and lenses of heavy plastic clay.
- C. 40-50 in. Light grey silt loam or heavy fine sandy loam, mottled brownish-yellow. Very variable.

GLEYSOL PODSOLS AND PEAT PODSOLS

When drainage impedance is superimposed on podsol development a *gley podsol* results. This is accompanied by an increase in the peaty layer which eventually leads to the development of a *peat podsol* profile. The drainage impedance may be due to ortstein development or to the formation of a clay pan by mechanical illuviation. Another possibility is swamping due to deforestation. I. V. Tiurin,

V. A. Burenkov, and A. S. Masslov¹² give an example of this from Russia. Where re-planting takes place the swamping gradually disappears in 15-20 years as the new stand of trees grows up. In the absence of re-forestation, it may be presumed that the original podsol character of the profile would become modified.

Scotland. A. Muir¹³ has described numerous profiles of gley podsolic and peaty gley podsolic (peat podsol) soils. The following example of a peaty gley podsol may be quoted. It occurs in lower Strathspey in the Teindland Forest. The parent material is boulder clay (till) and the vegetation *Calluna*, *Scirpus*, *Erica tetralix*, *Carex* spp., *Cladonia* spp., *Sphagnum compactum* in hollows, and stunted pine scrub. The altitude is 700 feet.

- A₀. 0-7 (10) cm. Surface root mat over black well-decomposed peat. Stones occasional.
- A₂-G. 7 (10-17) cm. Dark grey, sandy; humus staining throughout. Stony and free; many roots.
- B₁. 17-23 cm. Brownish-black humus accumulation layer, sandy and stony, roots numerous. Underlain by discontinuous hardpan which is quite thin.
- B₂. 23-38 cm. Iron-stained sandy, stony, roots occasional, structureless, slightly compacted yet appears free. Slight humus staining.
- B₃. 38-53 cm. Lighter in colour than previous layer, no humus staining visible. Fairly compact, stony and structureless.
- C. 53-80 cm. Purplish-red till, stony, structureless; slightly compacted.

The principal analytical data are :—

	A ₂ -G	B ₁	B ₂	B ₃	C
Ignition loss %	4.70	13.53	9.36	2.80	2.59
Clay SiO ₂ /Al ₂ O ₃	2.25	1.75	1.80	1.48	1.98
„ SiO ₂ /R ₂ O ₃	1.89	1.15	1.25	1.25	1.65
„ Al ₂ O ₃ /Fe ₂ O ₃	5.25	1.92	2.27	5.44	5.00

Wales. Gley podsols and peat podsols are widely distributed throughout Wales. In many cases they occur in situations where heath vegetation on freely drained soils has been succeeded by moorland vegetation with drainage im-



Photo. H. C. Davis

I

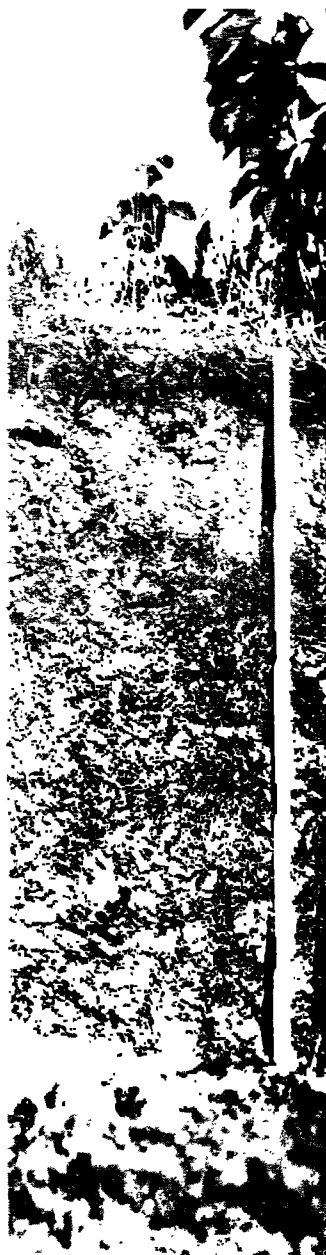


Photo U.S. Dept. Agric. Soil Survey Division

II

I Pakihi (Gley-podsol) profile, Nelson Province, New Zealand II Solon profile in lacustrine clay, N. Dakota, U.S.A.

PLATE VII.]

[To face page 363

pedance and peat formation. Such soils are common at high altitudes. The following profile is described by T. Wařowicz¹⁴.

N.E. of summit of Foel Fras at 3,000 feet, under vegetation of *Juncus squarrosus*, *Calluna vulgaris*, *Molinia cœrulea*, mosses, *Empetrum nigrum*, *Vaccinium myrtillus* and *Nardus stricta*.

A₀. 0-90 cm. Dark brown wet fibrous peat.

A₁. 90-100 cm. Grey silty loam with bleached gravel.

B. 100-105 cm. Rusty-brown gravelly loam, the intensity of the colour increasing with depth, passing to shattered rock.

The analytical data are as follows:—

		Exch.	Clay	Org.	Clay fraction		
		CaO		Carbon	SiO ₂ /Al ₂ O ₃	SiO ₂ /R ₂ O ₃	Al ₂ O ₃ /Fe ₂ O ₃
A ₁	3.88	tr.	6.6	3.0	2.41	2.13	7.69
B	4.47	tr.	9.0	2.2	1.19	0.75	1.68

New Zealand. T. Rigg¹⁵ describes certain soils, termed Pakihi soils, occurring in the Nelson province which appear to be essentially gley-podsols.

The following is a description of a Pakihi soil (see Plate V) under *Gleichenia dicarpa*, *Cladium teretifolium*, *Juncus planifolius*, *Lycopodium* and *Drosera* spp.

- (1). $\frac{3}{4}$ in. of raw humus.
- (2). $3\frac{3}{4}$ in. of grey sandy silt.
- (3). 5 in. of brownish fine sand merging into coarse sand.
- (4). 1 in. of coarse grit.
- (5). 4 in. of pan cemented with iron and humus compounds over gravel and stones stained in neighbourhood of pan.

VLEI* SOILS

This name has been given to certain African soils which occur in depressed or basin-shaped areas subject to seasonal wetness. They may be black, brown, or grey in colour and often show mottling due to the prevalence at certain seasons

*This Afrikaans word, pronounced *flay*, may be conveniently used for the tropical and sub-tropical analogues of the gley soils. The alternative term *mbuga*, used by Milne, might serve but is less euphonious.

of waterlogged conditions. Ironstone concretions (murram) are frequently present, and calcium carbonate nodules are also encountered.

Kenya. D. S. Gracie¹⁶ gives the following description of a profile in the South Thomson's Falls district of Kenya:—

- 0-9 in. White soil with mottling. Poor accumulation of organic matter at the surface. A band of iron concretions separating this layer from the next.
- 9-31 in. Compacted organic clay layer, whitish at first, but shading into black and becoming brown at its lower limit.
- 31-60 in. Yellowish material, soft and friable in the first six inches, then becoming harder. Large calcium carbonate concretions present.

The surface soil has a pH of 4.11 and contains 0.183% nitrogen.

Tanganyika. G. Milne¹⁷ describes a typical vlei soil in a saucer-shaped depression at Muhesa, Tanganyika. The altitude is 600 feet and the rainfall 50 inches, with maxima in March-May and November-December. The original vegetation was tall dense grass. The profile is:—

- 0-4 in. Friable grey-black surface soil.
- 4-10 in. Inky black sticky subsoil.
- Below 10 in. Mottled yellow soapy clay to 11 feet.

There are many ferruginous concretions through the subsoil and traces of calcium carbonate from 18 inches downwards. The following data for the Muhesa vlei soil were obtained in the writer's laboratory (Table XXXIII).

TABLE XXXIII.—ANALYTICAL DATA FOR MUHESA VLEI PROFILE

Depth	Clay %	Organic Carbon %	pH	Clay Fraction		
				SiO ₂ /Al ₂ O ₃	SiO ₂ /R ₂ O ₃	Al ₂ O ₃ /Fe ₂ O ₃
0-4 in.	27.6	2.99	7.6	2.99	2.47	1.62
4-8 in.	31.9	2.56	6.9	2.92	2.36	1.66
26-32 in.	45.5	0.85	6.3	2.15	1.79	5.00

Cuba. An example from Cuba of what would appear to be an analogue of the vlei soils is furnished by the Maboá series of H. H. Bennett and R. V. Allison¹⁸. These soils are developed on outwash from siliceous rocks in regions of flat topography with poor drainage. The profile consists of:—

- 0-3 in. Grey silt loam or fine sandy loam with some rusty brown mottling. Acid reaction.
- 3-8 in. Friable yellowish-grey or mottled pale yellow and grey material.
- 8-12 in. Pale yellow and friable material with abundance of perdigón (concretions).
- >12 in. At less than two feet. Mottled red and bluish-grey plastic impervious heavy clay.

The Coxville series of Cuba is similar to the Maboá series, but concretions are comparatively rare.

S. Rhodesia. H. B. Maufe¹⁹ describes a vlei soil derived from dolerite at Salisbury, S. Rhodesia. The profile consists of:—

- 0-9 in. Black soil.
- 9-28 in. Black clay subsoil.
- 28-43 in. Yellowish-brown clay with rounded blocks of fresh dolerite.

The top soil is coarsely granular, but the subsoil has a columnar or prismatic structure. Although the pit in which this profile was seen was waterless at the end of the dry season, the bottom part was distinctly wet, indicating poor drainage conditions. In a better drained situation in the immediate locality, the same rock gives rise to a red soil.

LATERITIC SOILS

These soils, developed under conditions of intermittent waterlogging either in contemporary or past times, have some claim to be included in the present chapter. In view of their widespread occurrence in the tropics, however, they have been retained in Chapter XIV.

GROUND-WATER PODSOLS

This term is given to a type of profile, developed generally in a light-textured material with a high water-table,

in which there is a strong bleaching of the A horizon and an equally marked deposition in the B horizon near ground-water level. The Leon series of Florida is described by C. E. Kellogg²⁰ as having "an exceedingly thin A horizon underlain by an acid, leached A₂ horizon of light grey fine sand, slightly stained with humus in the upper part. The B horizon is sandy, but darkly stained and cemented, largely with organic material, into a hard ortstein. The roots of plants are confined to the A horizon. . . . The water-table stood at about 3 feet where the B horizon merges into wet loose sand." Certain soils in San Domingo, described by E. Balzarotti²¹ as podsolized, may be similar and owe their characters to ground-water effects. They occur under savannah.

ALLUVIAL AND SWAMP SOILS

Soils derived from marine, estuarine, and river alluvial deposits can show all stages of development according to their age. Where time has sufficed, development can occur on alluvial material just as on any other kind of parent material. It would therefore be incorrect to describe a podsol developed on alluvium as an alluvial soil. The term is best restricted to juvenile soils with undeveloped profiles in which the soil characters are dominated by the parent material.

Agriculturally, these soils are of considerable importance. They are found in most countries and are generally of high fertility. Examples are the polder soils of Holland and the delta soils of Egypt. In many cases these have been reclaimed from tidal water by means of dykes. A considerable proportion of Holland has been thus won from the sea. The soils of older reclamations have undergone considerable changes. In the early years there is a leaching out of soluble salts, followed by a gradual loss of calcium carbonate and fall in base status. With skilful management, including the regulation of water conditions by drainage, these soils are very productive. In England the fertile agricultural soils of S. Lincolnshire are of this class.

In many parts of the tropics, mangrove swamps occur in coastal districts. These are sometimes reclaimed and used for paddy (rice) cultivation. Tropical swamp soils have, as yet, been insufficiently studied; but they present many points of interest. H. C. Doyne and R. R. Glanville²², in a study of mangrove swamp soils in Sierra Leone, found pH values of less than 3 in recently cleared soils. This intense acidity appears partly to be due to the presence of free hydrochloric acid from the hydrolysis of soluble ferrous salts. (See also p. 159.) The acidity of the top soil decreases after a few years of cultivation, but remains in the subsoil.

BLACK PRAIRIE SOILS

There is a group of soils in Canada and the United States, termed *black prairie soils*, which appear to be essentially meadow soils. In a description of Saskatchewan soil profiles, A. H. Joel²³ mentions a type of "black park land" profile, consisting of a "black or almost black A horizon of mixed loose and fine granular structure; a B horizon of some shade of brown, heavier and more compact than the surface, frequently somewhat columnar in structure and usually fine to medium granular when crumbled; a B₂ horizon of grey to light grey colour, frequently with a yellowish or brownish tinge and flowing to granular structure (zone of carbonate accumulation); and a C horizon of grey to dark grey colour mottled with flecks or stains of reddish-brown ferric oxide and frequently with concretions or splotches of calcium carbonate, calcium sulphate or both. The C₂ horizon is usually a more uniform dark grey or somewhat bluish dark-grey." A shallow and a deep phase are distinguished, the deep phase occupying lower elevations. Whilst the shallower phase is considered to be well drained and may be a type of chernozem, the deep phase shows evidences of poor drainage conditions in iron stains and mottlings. The black layer varies from about 3 to 8 inches in the deep phases. It is thus rather shallower

than in typical chernozems to which, on the grounds of carbonate accumulation, these soils might be assigned.

From this circumstance and the analytical evidence of mechanical and chemical eluviation, Joel excludes them from the chernozem group. It would appear that the deeper phases, at least, must be assigned to the meadow soil group.

Black soils in Alberta, described by F. A. Wyatt and J. D. Newton²⁴, show a somewhat similar profile, with an organic layer of about 12 inches in thickness overlying about 30 inches of grey columnar to granular clay loam or clay, with carbonate accumulation in the lower 6 inches. This is underlain by light yellow clay with occasional iron stains. The data for the nitrogen content of successive layers, both of the Saskatchewan and the Alberta black soil profiles, show a sharp decrease in organic matter in passing from the dark layer. This is markedly different from the gradual decrease in organic matter with depth observed in the chernozems and suggests the effect of impeded drainage conditions.

Considerable discussion has centred round the so-called prairie soils of the Middle-West of the United States. Whilst many of the European workers assign them to the meadow soils, C. F. Marbut²⁵, whilst admitting that, in the earliest stage of topographical development, impeded drainage may have obtained, considers the present drainage to be unimpeded. There are, however, areas in South-Central Iowa, North-Eastern Missouri, and parts of Southern Illinois where meadow soils occur owing to the survival of drainage impedance.

China. C. F. Shaw²⁶ refers to a class, known as Sajong soils, occurring in the central plains of China. They occur with an almost level topography. They show horizons of calcium carbonate accumulation at depths varying from one to six feet. From the description of the drainage conditions, it seems likely that they belong to the meadow soils rather than to the chernozem group. The calcium carbonate

would thus represent a deposit in the vicinity of a water-table.

S. AFRICAN BLACK TURF SOILS

There is a class of soils occurring typically in the Transvaal, but also found with no essential difference in Southern Rhodesia, to which the name *black turf* has been applied. The profile consists of a variable depth, commonly about three feet, of grey-black or brownish-black clay, granular when dry but waxy when wet. Calcareous concretions occur in the lower part of the layer, increasing in number to form eventually a friable calcareous layer, below which there is a transition to decomposing norite rock. In some cases the calcareous layer is absent and the black layer rests directly on the decomposing rock.

B. de C. Marchand²⁷, in a discussion of the origin of these soils, controverts the theory advanced by C. F. Marbut²⁸, that the black turf soils belong to the chernozem group, as might be expected from their black colour and the presence of a layer of carbonate accumulation. He shows that their occurrence is strictly associated with the outcrop of norite rock, whilst, under identical climatic and topographical conditions, diabase yields a completely leached friable red loam. They cannot be described as vlei soils since they are not limited to areas of depressed topography. The critical factors in their formation appear to be impeded percolation, consequent on the impervious character of the clay formed by the weathering of the norite, and their high base status, which results in the development, as elsewhere in hot climates, of a dark type of organic matter. The dark colour of these soils may convey an erroneous impression of their organic matter content, which is not generally higher, and may in some cases be actually lower, than that of the adjoining red loams.

The clay fraction of the black turf soils reflects the restriction of percolation, for it is markedly siliceous in character. Whilst the clay fraction of the leached friable red

loams has a silica-sesquioxide ratio of 2.0 or less, the clay fraction of the black turfs has a silica-sesquioxide ratio of 3.0 or more. The high base-status is also contributory.

C. R. Van de Merwe²⁹ considers these soils to be morphologically akin to the Indian regur and the black cotton soils of Kenya.

CONDITIONS OF DEVELOPMENT OF GROUND-WATER SOILS

In the present chapter, we have discussed soils with impeded drainage from regions with widely differing climatic conditions. Whilst they occur more frequently in humid regions such as North-West Europe, they may be found also under comparatively dry climates such as that of the Canadian prairies. The common characters that distinguish them are greyish to black surface horizons sharply defined from the sub-surface horizons, which, by their gleying, iron stains, mottlings, or concretions, and also, in many cases, by the presence of gypseous or calcareous horizons, give evidence of the alternation of aerobic and anaerobic conditions due to variable ground-water levels. The deposition of hydrated ferric oxide may often reach notable proportions, as in the soft bog iron-ore of northern lands and the harder "murram" or "mocarrero" of the tropics.

Soils developed under conditions of impeded drainage may, in some cases, show resemblance to the black earths. The relatively high content of organic matter often developed under neutral or alkaline conditions may result in a dark colour in the surface horizons. Further, the drainage impedance and the high base-status both tend to the development of a siliceous type of weathering complex analogous to that of the chernozem group. Finally, the presence of a ground-water table may in many cases be associated with the deposition of calcium carbonate in the adjacent horizons.

Meadow and vlei soils are, however, distinguished from the chernozems by the absence of the granular structure and

by the occurrence of rusty mottlings or streaks, indicating the alternation of oxidative and reductive conditions.

In the soils of this group examined by the writer, the mineral colour of the surface horizons is generally grey and never red or reddish-brown. Such analyses as have been made show the clay complex to be of a siliceous type with silica-sesquioxide ratios in excess of 2.0. It would be of interest to determine whether this is a constant feature.

PEAT SOILS

Peat soils are distinguished by the high proportions of organic matter which they contain. They are soils in which the residues of natural vegetation are humified rather than oxidized. A distinction is sometimes drawn between peat soils and mineral soils, but it is somewhat difficult to assign a limiting content of organic matter above which a soil is to be considered a peat. Whilst 15% of organic matter may suffice to give a pronounced peaty character to a light sand, a heavier soil may contain up to 20% of organic matter and still retain the appearance and character of a mineral soil. Typical peats, however, generally contain at least 50%, and may in some cases consist almost entirely of organic matter.

The humification that results in the formation of peat is, except in the case of heath peat and forest peat, of an anaerobic character, and takes place either under water, as in the formation of fen peat, or in situations where water-logging and consequent exclusion of air is the rule. From this it follows that peat is most readily developed under cool humid climates. But whilst they are commonly found under such conditions, peats can occur in the tropics, as for example, in mangrove swamps. Notable deposits of peat occur under sub-tropical conditions in the Everglades of Florida.

Typically, peats are formations of temperate and cool climates. They are more widespread in northern regions, partly because of the extensive spreads of glacial drift with its associated lakes, and partly because the scanty evapora-

tion associated with low temperatures results in a greater proportion of the rainfall being available as soil-water.

Most of the peat of Northern Europe and America has been formed in basins formerly occupied by lakes. Existing deposits represent different stages in a process which has proceeded since the close of the Glacial Period and is still in progress. The relationships of the different types of peat to each other will be evident from a description of this process.

The first stage of basin peat formation takes place under lacustrine conditions. In the shallow water near the shore, associations of such plants as *Phragmites*, *Carices*, *Juncus spp.*, and *Equisetaceæ* become established. The residues of these plants accumulate at the bottom, where they are mixed to some extent with lake mud and undergo anaerobic decomposition. The littoral association encroaches more and more on the free water surface until the lake is completely filled up by the humified residues of the plants which have inhabited it, mixed with a certain proportion of mineral matter carried by the stream feeding the lake and deposited as sediment. Examples of all stages of this process may be seen in any region of shallow lakes. The peat thus formed is known as *low-moor* or *fen peat* ("Niederungsmoor" or "Flachmoor").

With the disappearance of the free water surface and the accumulation of humified material, a gradual change in the type of vegetation sets in: mosses (e.g., *Hypnum*), *Calluna vulgaris*, *Erica tetralix*, *Molinia cœrulea*, and finally trees, such as alders (*Alnus*), birches (*Betula nana* and *pubescens*) and pines (*P. sylvestris* and *uliginosus*) make their appearance, whilst the earlier lacustrine plants die out. The peat accumulated from the residues of the new vegetation is now of a different type and may be recognized, when this stage is past, by the presence of tree remains.

The conditions at the close of the fen stage and before the establishment of tree growth are relatively dry, owing to the growth of the peat deposit above the original water level. The establishment of tree growth, however, by protecting

the surface layers from losses by evaporation promotes uniformly moist conditions allowing the growth of sphagnum moss. Meanwhile, there has been a progressive decline in plant nutrient status. The plants which contribute to fen peat are relatively rich in plant nutrients and grow in water containing considerable proportions of mineral matter in solution and suspension. As the peat grows above the fen level and contributions from telluric waters are diminished, the type of vegetation which prevails consists of plants which make scanty demands for nutrients from the medium on which they grow. The peat formed from their decay becomes progressively poorer in nitrogen and mineral constituents. This, and the wetness consequent on the high retentivity of the sphagnum for moisture, eventually results in the annihilation of tree growth, and the peat deposit now enters on its final phase as a *high-moor peat* or *bog* (Hochmoor) in which the principal plants are sphagnum species and cotton grass (*Eriophorum*).

In a fully developed profile, a section will disclose a complete succession from the beginning of the fen peat stage. W. Bersch³⁰ gives the following typical example :—

1. Vegetation layer.
2. Younger moss peat, 140 cm.
3. Light coloured transition layer (heath), 20 cm.
4. Older moss peat, 170 cm.
5. Woody peat, 85 cm.
6. Fen peat (*Phragmites* and *Carices*), 70 cm.
7. Peat mud, 15 cm.
8. Mineral horizons.

Horizons 1 to 4 represent the high-level peat; horizon 5, the transition (woodland) stage; and horizons 6 and 7, the fen peat. The transition layer between the older and the newer peat moss is generally observed in continental high level peats and is considered to represent a period of relatively dry conditions involving an intermission of sphagnum peat formation, and the establishment of heath.

Peat deposits may reach to a depth of 50 feet or even more. The rate of accumulation has been variously esti-

mated. Whilst the vertical rise of the surface may amount to 1-2 cm. per annum, the actual growth of solid peat must be considerably less. An estimate may be gathered from an example at Laibach, given by Bersch, where a Roman road of about the first century A.D. was found below 120 cm. of peat. Assuming 1,800 years as the upper limit of time, the rate of accumulation is about 0.7 mm. per annum.

Lacustrine or fen peat is markedly different in character and composition from sphagnum or bog peat, for not only are the plants from whose remains it has been formed richer in ash constituents, but there is also an admixture of sedimentary material of terrestrial origin.

S. A. Waksman and K. R. Stevens³¹ examined samples of lacustrine and sphagnum peats and their results given in Tables XXXIV and XXXV show clearly the contrast in composition between the two types. (Cf. pp. 203 *et seq.*)

TABLE XXXIV. — PERCENTAGE COMPOSITION OF SEVERAL HORIZONS OF A LOW-MOOR PEAT PROFILE FROM NEWTON, NEW JERSEY, U.S.A., ON BASIS OF DRY MATTER (WAKSMAN AND STEVENS)

Horizon	Ether-Soluble Fraction	Water-Soluble Fraction	Hemi-Celluloses	Cellulose	Lignin	Crude Protein	Ash
A ₁	0.66	3.08	10.31	0	38.35	22.48	13.22
A ₂	1.10	1.24	8.95	0	50.33	18.72	10.13
A ₃	0.49	2.31	7.02	0	57.83	14.81	10.15
A ₄	0.78	1.14	7.51	0	42.10	19.81	15.00
Lake peat ...	0.67	0.81	12.14	0	33.25	19.38	24.87
Bottom mud	0.36	1.24	5.92	0	15.62	9.81	59.55

The first point to be noticed is the contrast in the ash contents. Whilst, in the low-moor peat, the ash varies from about 10 to 25%, in the high-moor, the ash is between 1 and 2%, rising in the woody peat, which represents a transition to low-moor, to over 5%.

Secondly, whilst cellulose is completely decomposed under the conditions obtaining in low-moor, the high-moor

TABLE XXXV.—PERCENTAGE COMPOSITION OF SEVERAL HORIZONS OF A HIGH-MOOR (SPHAGNUM) PEAT PROFILE FROM OLDENBURG, GERMANY, ON BASIS OF DRY MATTER (WAKSMAN AND STEVENS)

Horizon		Ether-Soluble Fraction	Alcohol-Soluble Fraction	Hemi-Celluloses	Cellulose	Lignin	Crude Protein	Ash
Younger sphagnum	1	3.08	...	16.88	19.44	34.04	5.23	1.72
"	2	6.12	...	11.09	13.62	49.56	5.11	1.85
"	3	3.96	...	16.24	19.91	38.26	6.58	1.50
"	4	5.02	...	15.44	16.38	40.72	6.11	2.36
"	5	4.99	...	15.12	17.14	43.82	5.10	1.82
Heath peat	...	7.60	...	8.44	9.76	54.38	7.00	1.71
Older sphagnum	1	5.73	...	9.08	12.38	52.50	5.78	1.38
"	2	5.18	3.87	9.48	9.63	53.30	6.20	1.13
"	3	4.28	3.52	10.86	13.74	45.21	4.26	1.16
"	4	5.17	3.72	10.82	10.42	52.62	5.63	2.22
Woody peat	...	5.69	5.13	4.91	4.08	59.86	9.08	5.03

peats contain between 10 and 20% of this constituent. The transition to low-moor is shown by the fall in cellulose to 4.08% in the woody peat.

Thirdly, the crude protein content of the low-moor peats, excluding the bottom mud, varies from 18.72 to 22.48%, whilst in the high-moor the range is from 4.26 to 7.00%, the woody peat indicating the transition with 9.08% of crude protein. The highest figure in the high-moor peat, 7.00%, is found in the heath peat, the so-called "grenzhorizont," which is a constant feature of continental high-moors and may indicate a dry period.

W. L. Davies³², in a comparison of the nitrogenous matter of peats, found evidence of more rapid protein degradation under fen conditions than in upland peat or high-moor conditions.

The complete succession from lowland peat, through forest peat, to upland peat can only be observed in basins or depressions formerly occupied by lakes. In other cases, development may begin at the forest peat or the upland peat stage.

CLIMATIC MOOR AND MOUNTAIN PEAT

There is a type of peat, termed by continental writers "Hangmoor," which is of common occurrence in mountainous regions. It is formed along slopes down which water is continually percolating from springs in higher ground. The character of the peat will depend on the nature of the percolating waters. Where these are poor in dissolved material, for example, surface water, or waters from highly acid rocks, the peat will be of the high-moor or sphagnum type. With richer waters, on the other hand, peats of the fen type may be developed, whilst in some cases trees may be established. Extensive deposits of acid peat of the upland type are found directly on boulder clay or colluvial material throughout the mountainous regions of Great Britain.

G. K. Fraser³³ proposes the term *climatic moor* for those types of peat whose development is not primarily dependent on topography but on climate. In very humid regions such as the mountainous regions of Scotland and Wales, the stable soil type is of a moorland (peat) character in which the tendency is for impervious waterlogged layers of peat to develop. He distinguishes three sub-groups, namely, (a) *Scirpus* moor. North-western type with evenly distributed rainfall and low summer temperature; (b) *Calluna* moor or *Calluna-Eriophorum* moor. North-central Scottish type with drier summer and higher evaporation; (c) *Molinia* moor. Southerly type. Warmer and drier summer and higher evaporation.

HEATH AND FOREST PEAT

These terms are sometimes applied to the accumulations of humus on the surface of heath and forest soils. As the term peat is now generally restricted to humic material developed under wet anaerobic conditions, it is better to abandon the use of the term for humus accumulations developed under aerobic conditions with strong leaching. For such accumulations the term raw humus is better. (Cf. p. 204.)

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CHAPTER XIII

SALINE, ALKALINE, AND SOLOTI SOILS

CONDITIONS OF OCCURRENCE

THE soils to be described in the present chapter occur most commonly, but not exclusively, under arid climates. They owe their distinctive characters either to the presence of an actual excess of sodium salts, or to the predominance of sodium among the exchangeable bases—the latter a consequence of the former presence in the soil of sodium salts. In some cases, potassium salts may be present in appreciable amounts, but it is unusual for soils to occur in which potassium is the dominant exchangeable base.

The most commonly occurring groups are the saline, white alkali or *solontshak** soils, and the alkaline, black alkali, or *solonetz* soils. To these must be added a third group, which has been brought to the notice of soil students by the Russian pedologists, namely, the *soloti*† or degraded alkali soils.

Before entering on a description of some representative types of these groups, it will be necessary to enquire into the conditions under which saline, alkaline, and soloti soils occur.

The first pre-requisite for their occurrence is the presence of sodium salts in the soil or the parent material. These originate usually from underground water in situations where the water-table is relatively near the surface. Such conditions occur generally in areas of basin-shaped topography. The salts may have originated directly from

*Also termed *solontchak* or *solonchak*.

†Also termed *solodi* or *soloth*.

the chemical weathering of silicates, resulting in the accumulation in the underground water of the soluble products of hydrolysis, or they may represent the vestiges of former seas or salt lakes. Stated generally, the most usual mode of origin is from saline telluric waters either in the vicinity of inland seas or salt lakes, or in depressions where the water-table is at or near the surface. In such cases there has usually been a change in the hydrological conditions. In primary saline soils, there has been a lowering of the water-surface whereby soils or their antecedent parent materials have emerged. In this way, for example, the saline soils of the Great Basin in the United States have originated, for they occupy an area formerly covered by the ancient Lake Bonneville, represented to-day by the Great Salt Lake. The fall in level has doubtless been accompanied by a concentration of soluble salts in the remaining water. A similar fall in water level is postulated also in the Caspian Basin.

In secondary or regraded saline soils, the salinization has taken place by a rise in the level of salt-bearing ground-water. This may have taken place naturally, as, possibly, in parts of Hungary; but more frequently it is encountered as a result of human interference. W. W. Mackie¹ records that in 1873 the water-table at Fresno, in the San Joaquin valley of California, was 65 feet below the surface and the soil was practically free of salts. As a result of irrigation without adequate under-drainage, the level of the underground water in 1888 was only 2-3 feet below the surface and the soil was definitely affected with "alkali." Similar instances can be found in most irrigated areas where large tracts of formerly fertile soil have been ruined through the rise of ground-water.

We may class with the secondary saline and alkaline soils, those which, without any marked change in water-table, have undergone change through the use of irrigation waters in which sodium is the predominant cation. The continued use of such waters leads to a gradual replacement of exchangeable calcium, by sodium, so that even although

no considerable proportion of sodium salts is present, the soil becomes a sodium soil. In arid areas near to the ocean salinization may occur through the addition of sodium chloride brought down in the rainfall. L. J. H. Teakle² estimates that the annual contribution of "cyclic" salt in W. Australian maritime districts may amount to 300 lb. per acre. In this connexion the existence of more pluvial conditions in past ages may be of importance. M. Gračanin³ attributes the salinity of certain soils in Adriatic islands to wind-borne salt.

SALINE SOILS

These soils are the *white alkali* soils of the earlier American writers, and the *solontshak* soils of the Russian school. They contain an excess of sodium salts, generally the chloride or sulphate, and have a flocculated structure. They occur usually in depressions, and the distribution of salts varies with the season. During drought, they show white efflorescences of sodium chloride or sulphate, from which the American term white alkali is derived. During rain, the salts deposited at the surface are dissolved and temporarily washed down towards the water-table. A considerable variety of possibilities presents itself; for the character of the soil will depend on the position of the water-table, the amount and distribution of the rainfall, the concentration and composition of the soluble salts, and the general character of the soil of the region. Saline soils occur most commonly in arid, semi-arid, and semi-humid regions and may represent modified chernozems, chestnut earths, or grey earths. Where the water-table lies so near to the surface as to maintain permanently moist conditions, saline peaty or saline meadow soils may result.

Russia. Saline soils are generally described by Russian writers as structureless in contradistinction to the structural alkaline (solonetz) soils. A typical profile from the vicinity of Akmolinsk is described by G. Tumin⁴ :—

- A₁. 0-1 cm. Light grey salt crust with carbonates, passing to a dark grey looser structureless horizon. Gradual transition to
- A₂. Brown with grey streaks and mottlings. Weak carbonate reaction. Numerous small flecks of salt to 30 cm. From 30-45 cm., larger flecks.
- C. Light brown salt bearing loam, containing carbonates.

The whole profile is moist and the saline ground-water is encountered at 110 cm.

Glinka⁵ describes a saline soil with affinities to the chestnut earths in the Jenisseisk province of Russia. The profile is as follows :—

- 0-1.5 cm. Loose dusty soil with plant roots.
- 1.5-9 cm. Rather more compact chestnut soil without marked structure.
- 9-19 cm. Lighter coloured than above horizon but especially porous.
- 19-44 cm. Lighter coloured and porous.

Finland. Saline soils may occur in humid regions where ground-waters containing salts may occur. B. Aarnio⁶ describes certain Finnish soils in which saline ground-water occurs. The following table shows the composition of the salts in different horizons of a typical profile consisting of :—

- 0-10 cm. Dark brown peat.
- 10-20 cm. Fine sand.
- >20 cm. *Litorina* clay.

At 15 cm., there is a gley horizon showing brown streaks in the sand, whilst the clay is coloured yellowish-brown. The reaction of the surface horizon is less than pH 4. Removal of salts by drainage involves a lowering of the water-table, which is more than 1 metre below the surface. Capillary rise of salts is inappreciable, a circumstance which is connected with the humid climate. Saline water at this depth in an arid climate would dominate the character of the soil.

Saline soils, since they often occur in situations where the water-table is comparatively near the surface, may be expected to show affinities with the meadow soils. This is

TABLE XXXVI.—SALTS IN VEGETATION-FREE SALINE SOIL, ISOKYRO, FINLAND (AARNIO)

Depth			0-10 cm.	10-20 cm.	25-35 cm.
Percentage Water-soluble Salts ...			2.45	0.20	0.22
SiO ₂	...	...	0.29	—	12.26
Al ₂ O ₃	...	...	10.77	7.32	3.66
Fe ₂ O ₃	...	...	0.31	—	—
CaO	...	...	23.77	13.24	12.44
MgO	...	...	1.65	6.92	10.89
K ₂ O	...	...	0.41	—	1.46
Na ₂ O	...	...	4.16	16.42	7.32
SO ₃	...	...	56.78	48.84	48.76
Cl	...	...	0.85	7.12	3.20
Total ...			99.99	98.86	99.99

shown in some profiles by the presence of rusty flecks or mottlings in the lower horizons.

In extreme cases, saline soils are devoid of vegetation, as for example, in the vicinity of the Great Salt Lake, and the Dead Sea. In other cases, there is an open association of halophytic plants such as salt bush. With lower contents of soluble salts there is a transition to the normal soil of the region, which may nevertheless exhibit the characteristic structural and chemical features of the saline group.

ALKALINE SOILS

These soils, which are closely associated with saline soils, are termed *black alkali* by the American workers and *solonetz* by the Russians. They are characterized by the presence of sodium carbonate. Whilst the saline soils are in a state of flocculation, the alkaline soils have a strongly alkaline reaction and are deflocculated. The presence of alkaline soils in an area of saline soils is marked by depressions corresponding with the decrease in pore-space implied by the change of structure. In these depressions,

during rain, alkaline solutions of humic matter accumulate and, on drying, leave black deposits which give to these soils the American name "black alkali." The development of solonetz from solontshak is termed *solonization*.

The alkaline soils are further distinguished by the development of a structure profile. Typically, this consists of a laminated superficial horizon overlying a deep layer showing a columnar (rounded tops) or prismatic structure. The rounded tops of the columnar elements and the vertical sides frequently carry a white mealy coating of salts. The soil colours are grey or greyish-brown throughout.

The "structure" of alkaline soils is a consequence of their deflocculated state. When wet, the whole body of the profile consists of structureless material in the single grain state. On drying, shrinkage occurs and prismatic or columnar structures develop.

Ukraine. The following data are cited by D. G. Vilensky⁷ for a profile in the Dnieper region:—

- 0-19 cm. Light grey, platy, fine sandy eluvial horizon. The surface of the plates is powdered.
- 19-29 cm. Illuvial, dark grey, columnar horizon (columns 8-11 cm.). The columns have rounded tops with a meal-like efflorescence which also appears in places on the vertical sides of the columns.
- 29-48 cm. Transitional prismatic.
- 48-78 cm. Accumulation of sulphates. Light loess-loam with minute inter-layers of gypsum.

Another profile described by Vilensky showed the following characteristics:—

- 0-1.5 cm. Humus horizon. Semi-peaty, grey-brown loam.
- 1.5-10 cm. Dark brown short columnar. Columns are 4 cm. in diameter, clayey, compact, and do not effervesce with acid.
- 10-27 cm. Rather lighter coloured, breaking into large pillars, heavy loam.
- 27-83 cm. Dark brown with grey spots of effervescent salts. Compact loamy.
- 83-100 cm. Muddy brown with very numerous white spots. Loose non-structural.
- 100-120 cm. Bluish-grey flowing sand with water at 120 cm. under pressure.

The above profile contains chloride and sulphate in the upper horizons.

Hungary. The Hungarian alkali soils (Szík lands) contain very small proportions (0.15-0.20%) of soluble salts. They exhibit impervious horizons, considered by A. A. J. De Sigmond⁸ essential to the formation of such soils. The contrast between alkali and non-alkali soils in the character of the exchangeable cations is shown by the data in Table XXXVII.

TABLE XXXVII. — EXCHANGEABLE BASES IN ALKALINE AND NON-ALKALINE SOILS (DE SIGMOND)

Soil		Milli-equivalents per cent.				
		CaO	MgO	K ₂ O	Na ₂ O	Total
Bad Alkali	{ Hortobàgy 1	2.60	1.34	0.94	9.62	14.50
	{ Békèscsaba 5	8.32	3.86	0.14	7.30	19.62
	{ Mezohégyes	17.65	2.54	0.55	4.68	25.42
Non-alkali	{ Keszthely 1	15.96	1.75	0.33	0.19	18.23
	{ Keszthely 22	15.18	1.82	0.41	0.12	17.53

Whilst, in the bad alkali soils, the proportions of Na₂O to the total bases are 66.35, 37.21, and 18.41%, respectively, in the non-alkali soils, the proportions are 1.01 and 0.41%, respectively.

United States. Solonetz or alkali soils are widely distributed throughout the arid regions of the west. The following is a description of a western N. Dakota solonetz by C. E. Kellogg⁹. The natural vegetation is western wheat grass, *Agropyron smithii*.

- A₁. 0-1½ in. Dark greyish-brown clay loam thoroughly permeated with roots.
- A₂. 1½-3 in. Very dark greyish-brown clay with hard coarsely granular structure.
- B₂. 3-14 in. Brownish-black clay with very hard prismatic structure. Prisms from 1 to 6 in. in diameter, breaking with difficulty into irregular sharply angular pieces. Upper part faintly mottled rusty-brown.

- B₃. 14-24 in. Very dark grey clay. Prisms much less distinct and soil more massive.
- C. 24 in. +. Very dark grey massive clay soil; digs out in large massive chunks with difficulty. Only a few vertical cracks extend into this material.

Some mechanical mixing of material occurs through surface soil falling into vertical cracks. Effervescence with HCl found below 30 in.

RELATIONSHIPS OF SALINE TO ALKALINE SOILS

The relationship of alkaline to saline soils is now intelligible owing to the investigations of Gedroiz, De Sigmond, Kelly, and others, on the base exchange reactions of these soils. The presence of an excess of sodium salts in saline soils results in the partial or complete replacement of their exchangeable calcium by exchangeable sodium. So long as excess of sodium salts is present they remain in the flocculated condition with neutral or slightly alkaline reaction. With removal of excess of sodium, the reaction becomes markedly alkaline and deflocculation occurs. The process has already been discussed in Chapter VI.

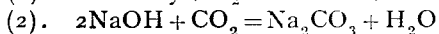
There is no hard and fast line of division between saline and alkaline soils, and all stages in the transition between the two types may be encountered. This, in addition to the great variety of possibilities in the conditions antecedent to salinization, results in very great variation in the character of these soils. The principal factors are, however, the position of the water-table, the composition of the ground-water, the nature of the soil and the degree of leaching, either naturally by rainfall or artificially by irrigation.

The problem of alkaline and saline soils is of the greatest importance for irrigated agriculture. Irrigation is usually practised in valleys and, unless special measures are taken to ensure drainage, the ground-water level rises, bringing sodium salts within the effective capillary range of the surface horizons. This leads in time to the replacement of calcium by sodium in the absorbing complex and, in addition, may involve such an increase in salt concentration in

the soil moisture as to inhibit plant growth. By the leaching action of irrigation water, the saline soil may become changed into an alkaline soil with deflocculation and increase in alkalinity.

In some cases the salinization may result from the irrigation water itself having excess of sodium over calcium ions, as is so frequently the case in S. Africa. The soil becomes changed from the calcium to the sodium soil with consequent deterioration in fertility.

It should be remarked that, although the presence of sodium carbonate is a characteristic of alkaline soils, the development of their distinctive properties is not dependent on the occurrence of large proportions of this salt. If, by the continued action of sodium salts, a soil is brought to the state in which the exchangeable calcium is replaced by sodium, the resulting sodium soil is potentially an alkaline soil and becomes deflocculated as soon as the concentration of the excess salts falls sufficiently low to permit the hydrolysis of the sodium clay. Under these conditions, sodium carbonate may be formed either by the reaction of the sodium clay with calcium carbonate, or by the action of carbon dioxide on the sodium hydroxide liberated by hydrolysis. These reactions may be represented by the equations:—



Sodium carbonate should thus be regarded as one of the consequences of alkalization rather than as the cause of the distinctive characters of alkaline soils. The percentage of sodium carbonate is in itself no measure of the degree of alkalization of a soil. If carbon dioxide be excluded, it is possible to prepare completely deflocculated soils from which sodium carbonate is entirely absent.

An example of the artificial alkalization of a soil by the action of sodium salts is seen in certain manurial plots at the Rothamsted station which have received repeated heavy

dressings of sodium nitrate. The soil has now become sticky and impervious, and exhibits some typical features of an alkaline soil.

D. S. Gracie, M. Rizk, A. Moukhtar, and A. H. I. Mustapha¹⁰ describe a type of akalination in which biological activity plays a part. In certain Egyptian soils containing gypsum the anaerobic condition consequent on a high water-table results in reduction of calcium sulphate and formation of ferrous sulphide. This is accompanied by an increase in alkalinity which depresses the solubility of calcium and magnesium compounds and facilitates the formation of the sodium soil. At the same time calcium carbonate and magnesium silicate are precipitated.

Russian workers have attached first importance to morphology in the diagnosis of solontshak, solonetz and related soils. The term solonetz, as first used, denotes a soil having a certain type of structure profile. This was found later to be associated with the chemical properties which have been described above. C. F. Shaw and W. P. Kelley¹¹ have directed attention to the fact that soils exist which have the solonetz structure but lack the chemical characteristics associated with solonetz. N. I. Usov¹² relates the occurrence of the physical properties associated with magnesium solonetz to the ratio of exchangeable calcium to exchangeable magnesium. With $\text{Ca}:\text{Mg} > 3$, physical properties are dominated by calcium; with $\text{Ca}:\text{Mg} < 2$, the soil is heavier and shows a coarser structure. Where more than 40% of the base exchange capacity is represented by magnesium the solonetzic properties are well developed, but to a smaller degree than in the case of sodium soils. J. H. Ellis and O. G. Caldwell¹³ also have described soils with solonetz structure containing little or no exchangeable sodium. It seems clear, therefore, that if the term solonetz is to be retained in its original sense, chemical composition must be assigned a subsidiary rôle. The writer would prefer to abandon the term as a description of a world group and use the term alkaline soil, which has a definite chemical significance.



[Photo, C. E. Killogg,
SOFODIZED-SOLOSETZ, N. DAKOTA.

SOLOTI OR DEGRADED ALKALI SOILS

The hydrolysis of sodium soil with production of sodium hydroxide involves also the formation of the hydrogen soil, as shown above. In the presence of excess of calcium carbonate, calcium soil is speedily re-formed, if indeed it is not formed by the direct inter-action of the sodium soil and calcium carbonate. In the absence of calcium carbonate, however, degradation of the hydrogen soil into silicic acid and sesquioxides occurs. The sesquioxides become leached out, leaving a bleached eluviated horizon relatively rich in silica. The process is in its results similar to podsolization, but the actual degree of destruction is greater. The A horizon of *soloti* soils may contain as much as 12% of free silica of secondary origin. The formation of soloti from solonetz is termed *solodization* or *solotization*.

A typical Russian soloti profile is described in the following terms by Korotky¹⁴:—

- A₀. Peaty layer with grass cover; 3-5 cm.
- A₁. Grey or ashen-grey layer with tongue-like projections from the peat layer; 1-10 cm.
- A₂. Whitish grey, with numerous rust spots, and ferruginous concretions; typical podsollic laminated structure; 10-15 cm.
- B₁. Brown varying to rusty or bluish-grey (humus); abundant humous mottlings; a sticky clay; numerous "ortstein" grains in the upper portion, forming in the lower portion a black or dark brown material (iron and manganese compounds); on drying breaks into prismatic lumps.

United States. C. E. Kellogg⁷ describes solodized solonetz soils in western N. Dakota. The following is an example. It is from the same region as the solonetz described on p. 385. A similar profile is shown in *Plate VIII*.

- A₁. 0-1 in. Brownish-grey loam with soft crumb or mulch-like structure.
- A₂. 1-3 in. Greyish-brown loam, platy and friable.
- B₁. 3-5 in. Dull greyish-brown silt loam. Relics of prismatic structure but distinctly platy. Easily friable to medium crumb structure.
- B₂. 5-8 in. Dark-brown clay with well-developed hard columnar structure. Cups of columns well developed.

- B₃. 8-12 in. Olive brown clay with irregular prismatic structure. Easily crumbling to sub-angular difficultly friable nut-sized pieces.
- B₃₁. 12-22 in. Olive-brown clay, similar to above, except that carbonates are present. Numerous white flecks and streaks.
- C₁. 22-26 in. Olive-grey sandy clay, highly mottled with white. Compact in places and digs out in brittle easily friable pieces.
- C. 26 in. + . Olive-grey sandy clay till, mottled white. Compact in places as above, but pieces become very hard on drying.

Saline, alkaline, and soloti soils occur commonly in close association often as complexes differentiated by relief forms and local hydrological conditions. C. E. Kellogg⁷ has studied such a complex association in western N. Dakota. The normal sequence of development is chestnut-brown earth→solonshak→solonetz→soloti→eroded soloti. With an erosion of the soloti profile, vegetation is re-established in the exposed B horizon and the normal profile may be re-constituted. In some cases regeneration may take place without intervening erosion. The distribution is exceedingly complex and a pronounced micro-relief develops through differential erosion of the eluviated horizons of the solonetz-soloti complex. A distinction is drawn between salinization by flooding and salinization by capillary action.

Saline and related soils occur most commonly in arid regions and are therefore associated most usually with pedocalic soils, where their occurrence is generally determined by topographical factors. They are extensively found in such areas as the Great Basin of the United States, the Caspian region of Russia, and the interior of Australia. They come most frequently to the notice of soil investigators through their development in irrigated tracts. It is a common experience in such regions that soils deteriorate under irrigation. This may be due either to the rise of a saline water-table or to the use of water containing excess of sodium salts. In many irrigated areas there are considerable tracts which have gone completely out of cultivation through alkalization.



[Photo C. L. Keweg]

SOLODIZED-SOLONETZ LANDSCAPE, N. DAKOTA

Whilst it is known that derelict alkali lands can be reclaimed by such methods as dressing with gypsum, in order to reconstitute the calcium soil, comparatively little has been done in practice to check deterioration in irrigated soils. The reclamation of such lands and the prevention of deterioration in land now under irrigated cultivation forms one of the most important tasks of applied pedology.

The reclamation of tidal or submerged lands involves the change of saline into normal soils. In Holland, the home of such works, the transformation is facilitated by the humid climate and by the presence of calcium carbonate in the soil.

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CHAPTER XIV

SOILS OF THE HUMID TROPICS AND SUB-TROPICS

GENERAL CHARACTERISTICS

THE devotion of a separate chapter to the discussion of tropical soils must not be taken to imply that they can be considered as in any way constituting a great world group. In fact, representatives of most of the recognized world groups can occur in the tropics, but the special conditions occurring in those regions, above all the high temperatures, result in certain distinctive soil characters. It is, therefore, convenient, if only for descriptive purposes, to consider them together. Certain soils occurring in the tropics, but more thoroughly studied in temperate regions, have already been mentioned. In the present chapter, therefore, we shall not deal with tropical pedocals, principally because in the present state of knowledge they are more conveniently considered along with the better known pedocals of temperate climates. If the increase of our knowledge of these soils made possible a fuller treatment, it might prove better to consider them together with the other soils of tropical regions. In the present chapter, therefore, we shall discuss only the soils of the humid tropics.

The most important circumstance differentiating the soils of the tropics from other soils is, of course, the temperature conditions under which they are developed. The mean temperature within the tropics is generally above 25°C , and in latitude 30° , is about 20°C . Bearing in mind that all chemical changes increase in velocity with rise of temperature, a rise of 10°C approximately corresponding with a

doubling of velocity, it is easy to understand that the hydrolysis of mineral silicates, which forms the most important process in chemical weathering, proceeds with much greater rapidity under tropical conditions.

In addition, there has been an absence, during recent geological time, of glacial interference. Tropical weathering has thus operated over a much longer period of time than weathering in regions such as Northern Europe, where it can only date from the close of the last glacial epoch. There is also no interruption of chemical action by winter, as in temperate and cool regions. It is not surprising, therefore, that the depth to which epigene weathering extends is considerably greater than in temperate and cool climates. It is not uncommon to find fifty feet or more of weathered material.

The A, B, and C nomenclature used in the description of soils of temperate regions has not been used so frequently by students of tropical soils. Indeed, in many cases considerable uncertainty may exist as to the depth of the solum, for there may be little apparent change below the top few inches. It might be justifiable to regard soils developed over deep layers of weathered material as secondary (see p. 65) in that the processes that have formed them from the parent rock date back in many cases through geological time, whereas soil profile development is mainly contemporary. Many of the distinctive characters of tropical soils are, indeed, attributable rather to the parent material than to the operation of present-day processes of profile development.

The parent material of tropical soils, being the product of age-long processes, is often in an advanced stage of weathering. Since hydrolysis of rock-forming silicates involves loss of silicic acid, alkalies, and alkaline earths, the parent material will tend to be markedly sesquioxidic in character, in other words to be ferrallitic rather than siallitic.

Although the general tendency is towards a ferrallitic product, the actual course of weathering may vary. The most typical case is where the first product of weathering,

adjacent to the decomposition rock is of a siallitic (kaolinitic) type, whilst the overlying horizons of weathered material are ferrallitic or, according to the nomenclature of certain writers, lateritic. On the other hand, F. J. Martin and H. C. Doyne¹ describe the weathering of norite in Sierra Leone, in which the first product appears to be ferrallitic. J. B. Harrison² also regards the primary process as resulting in a ferrallitic (lateritic) product. The difference may be attributable to the parent rock in that the primary product is generally siallitic in the case of acid rocks and ferrallitic in the case of basic rocks.

One circumstance, possibly fortuitous, that tends to colour our views on tropical soils is that so much of the published data relate to soils developed in material derived from the weathering of igneous rocks. On the other hand much of the best known work on the soil of temperate regions, including most of the Russian and Central European work, relates to soils derived from secondary materials such as loess, glacial drift, and alluvium. It is possible that some, at any rate, of the characteristics commonly associated with tropical soils may be attributable to the type of material from which they have been developed, rather than to the particular conditions of profile formation.

Tropical soils often consist almost entirely of the products of chemical weathering, together with a greater or less admixture of unweatherable minerals such as quartz, magnetite, etc. Weatherable minerals such as feldspars and ferromagnesian minerals, are, in some cases, almost entirely absent. Such soils, if derived from basic rocks that do not contain quartz, may contain very high proportions of clay, as much as 80% being by no means uncommon.

Coming now to the actual processes of profile development we have, as in the case of weathering, the effect of the high temperatures, which not only favour plant growth but also those chemical and biological processes whereby plant residues undergo oxidative decomposition. We shall return to this later.

Of equal importance with temperature in determining the type of profile development in the humid tropics is the character of the rainfall. Equatorial regions have generally high rainfalls, but two peculiarities must be noticed.

Firstly, the rainfall tends to fall in heavy downpours, exceeding in intensity the heaviest rain encountered in higher latitudes. There are instances of as much as 6 inches of rain falling in an hour. Such intensity of rainfall can cause a strong erosion, particularly where the natural vegetative cover has been removed as a preliminary to cultivation. This leads to the development of extensive alluvial and colluvial fans in valleys. A further consequence of the prevalence of erosion is the production of truncated or immature profiles. Many of the difficulties which present themselves in the study of tropical soils might be obviated if the part played by erosion were more clearly appreciated.

Secondly, except in the regions of tropical rain forest, where rainfall prevails throughout the year, there is a general tendency for tropical humid climates to be divided into well marked wet and dry seasons. During the wet season, leaching by percolating waters may occur, resulting in a general impoverishment in bases and the production of acid profiles with consequent instability of the clay complex. The conditions during the dry seasons are totally different. By reason of the high temperature, evaporation is very intense and the soil becomes rapidly dried out to a considerable depth. Such climates are sometimes termed "monsoon" climates.

The prevailing colour of freely drained tropical soils is red, the actual tinge varying somewhat according to the amount of organic matter present and the mutual effect of the parent material and the pedogenic processes. In basin-shaped areas with impeded drainage, and also where the parent material has a high lime status, dark-coloured or grey soils may result. It may be assumed that both the processes affecting the inorganic weathering complex and the decomposition of plant residues proceed differently according

as the soil profile is developed with free or restricted drainage.

Red soils appear, then, to result under conditions of free drainage and low lime status. Contrary to the impression produced by their bright red colour, such soils, until they are cultivated, may contain appreciable proportions of organic matter, particularly where the natural vegetation forms a close association such as forest, forest steppe, or savannah.

Topography has a marked effect on profile development. Whilst upland areas of convex topography are strongly leached and more or less eroded, lowland areas with concave topography are permanently or seasonally wet and carry soils having affinities with the gley soils of temperate climates. This often results in a characteristic pattern in which the elevated areas are occupied by freely drained red soils and the depressions by grey or black soils with impeded drainage.

Soils subjected to submergence undergo characteristic changes, provided sufficient organic matter be present. Under these conditions, anaerobic decomposition occurs and rapid losses may ensue. There is also an increase in the solubility of the iron, manganese, calcium and magnesium, which are changed to hydrogen carbonates, the iron being in the ferrous state. The reductive processes result in a change from the red colour of well aerated soils to the grey colour associated with bottom soils. Where water movements can occur, the dissolved bases may be lost from the soil with consequent impoverishment.

The rôle of organic matter in tropical soil formation has been discussed by E. C. J. Mohr³. The amount of organic matter in a soil represents the balance between the addition of material in the form of plant residues and the destructive oxidation of added material by micro-organisms. The general relationship between plant growth and temperature may be expressed by a curve having its minimum at about 0°C, its optimum at 25°C and its maximum at something over 40°C. Given adequate moisture conditions, we may

expect the maximum production of organic matter and, therefore, the maximum addition of plant residues at about 25°C. The curve connecting micro-biological activity with temperature shows a different course. The minimum lies somewhat above that for the growth of the macro-flora. Mohr places it at about 10°C, but this is probably too high. The optimum lies at about 35-40°C, whilst the maximum may lie at 70-80°C, well above the temperatures encountered in actual soils. Mohr distinguishes micro-biological decomposition under aerobic and anaerobic conditions, the intensity of decomposition being considerably greater under aerobic conditions.

Considering, now, the course of accession and destruction of organic matter in aerobic soils, the positive balance between the two processes increases up to about 20°C, after which the rate of destructive microbiological action increases more rapidly than plant growth with rise in temperature, until at somewhat above 30°C, destruction is sufficiently rapid to keep pace with additions of organic matter.

Under anaerobic conditions, less intense decomposition leads to the maximum balance between accession and destruction occurring at a higher temperature. The point at which gains are balanced by decomposition lies at about 35°C.

From the above considerations, it might be expected that virgin tropical soils with good aeration would have a very low organic matter content. This is by no means always the case. In the examination for another purpose of a range of soils, which included many samples from E. Africa and other parts of the tropics by G. W. Robinson and M. Richardson¹, organic carbon contents were determined and the figures obtained were not markedly lower than those to be expected from a similar textural range under British conditions. Further investigation is necessary, but it may be tentatively suggested that, although plant residues undergo rapid decomposition under tropical conditions, the actual humus is more resistant. The recurrent drought occurring

under monsoon climates may be conservative of soil organic matter as in the case of the chernozems.

The humus of tropical red soils is generally paler in colour than that of soils in temperate regions. G. Milne⁵ reports that soils from Tanganyika with about 4.1% organic carbon are not markedly humous in appearance. He considers that this humus has little crumb-forming effect.

Except in regions of continuous rain, the humid tropics generally have marked wet and dry seasons. During the dry seasons, the soil moisture becomes relatively concentrated and tends to move upwards to the surface where it evaporates. There will thus occur a precipitation of materials from solution, principally in the surface horizon, which thus becomes an horizon of accumulation. The precipitation which occurs will be to some extent irreversible and result in the formation of the concretions which are such a distinctive feature of tropical soils. On the side of increasing humidity, concretionary deposits will tend to become less frequent.

H. H. Bennett and R. V. Allison⁶ have analysed the concretions (*perdigón*) from some typical Cuban soils. They are often markedly sesquioxidic in character but always contain a certain amount of silica. In some cases the silica may amount to over 50%. Such concretions are similar in composition to fairly siliceous clays.

Tropical soils frequently show an increase in acidity, as measured by pH value, in descending the profile. This has been discussed by H. C. Doyne⁷, with special reference to Nigerian soils.

RED LOAMS AND RED EARTHS

As has been mentioned above, mature soils developed in the tropics under conditions of free drainage are generally red in colour. Tropical red soils are often loosely termed lateritic. The term laterite has been used in many senses, and in the sequel we shall attempt to restrict its application to one particular type of profile to be discussed at a later

point in this chapter. The red colours of tropical soils may be attributed to the presence of free ferric oxide in one or more of its different forms. Some red soils may contain very high proportions of ferric oxide, but this cannot always be inferred from their colour. Free alumina is also present in notable proportions in many tropical soils. For soils with high proportions of sesquioxides the term *allitic* was proposed by A. Harrassowitz⁸ in contrast with soils having a more siliceous type of weathering complex which are termed *siallitic*. In the present account we shall use the term *ferrallitic* in place of allitic to denote soils containing high proportions of sesquioxides in the weathering complex. A completely weathered soil, i.e., a soil in which the weatherable minerals have undergone complete desilicification with a resulting weathering complex consisting only of sesquioxides may be termed *ferrallite*. We consider these terms preferable to *lateritic* and *laterite*, used by many earlier authors but open to objection by reason of their lack of precision. Finally, it would appear desirable to restrict the terms siallitic, allitic, and ferrallitic to the description of soils as materials rather than as profiles.

If it be assumed that weathering under humid tropical conditions can produce a residual complex with an excess of sesquioxides, variations may occur according to (a) the extent to which desilicification has occurred, and (b) the extent to which the soil or its individual horizons have received accessions of sesquioxides by illuviation. Apart from the most extreme ferrallites, which must be regarded as exceptional cases, tropical red soils always contain some silica in the clay complex and the presence of aluminosilicic clay constituents must be assumed.

The investigations hitherto made by X-ray methods on the clay complex have not disclosed any minerals having molecular $\text{SiO}_2/\text{R}_2\text{O}_3$ ratios less than 2.0. Whilst S. Mattson⁹, by removal of excess sesquioxides, using hot aluminium chloride solution, obtained a residue of the halloysite type, the amounts of free sesquioxide found by

F. Hardy¹⁰ in tropical soils would imply the presence of minerals having $\text{SiO}_2/\text{R}_2\text{O}_3$ ratios less than 2.0.

P. Vageler¹¹ draws a distinction between *red loams* and *red earths*. We have seen that the tendency of weathering under tropical conditions is towards the production of a weathering complex relatively enriched in sesquioxides by the removal of silicic acid or by accession of illuvial sesquioxides. In comparatively young soils these changes are not far advanced. The clay is of a siliceous type and the soil is described as a red loam. In the red earths, removal of silicic acid or accession of sesquioxides has proceeded sufficiently to give a weathering complex of a predominantly sesquioxidic character. A. Eichinger¹² distinguishes three stages in soil development under humid tropical conditions, namely, *younger red earth*, *older red earth*, and *laterite*. All three types may occur under a uniform forest cover and the differences only become apparent after the institution of cultivation.

A red loam profile (Eichinger's younger red earth) consists of a deep and uniform layer of fairly plastic clay, often with yellow mottlings in the lower horizons and a gradual transition through a zone of decomposition to the parent rock.

The distinction between red loams and red earths has been used by many writers, notably by the late G. Milne. Although red earths as materials represent a more advanced stage of chemical weathering than red loams, it should not be assumed that they are necessarily more mature as soils, as might seem to be implied by Eichinger's nomenclature. The difference in development relates merely to the parent material. The soils of the south-eastern United States described as red podsollic soils would appear to be akin to, if not identical with, the tropical red loams. The redness is essentially a quality of the parent material, for the superficial horizons may show some bleaching.

Cuba. The soils of the Limones series in Cuba,

described by H. H. Bennett and R. V. Allison¹³, may be cited as examples of the red loams. The profile consists of :—

- 0-4 in. Reddish-brown to dull red clay; cracking into hard clods on drying.
- 4-12 (18) in. Pinkish-red clay, cracking in dry season. Fragments of parent rock present in lower parts of horizon.
- 12 (18)-24 in. Partly decomposed soft serpentine rock, greenish or bluish or hard rock.

The pH given is 6.72, the figure presumably referring to the surface soil. No data are available for the composition of the colloidal clay, but the silica and sesquioxide figures for the total soil of two successive layers are as follows :—

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃
0-16 in.	51.25	17.40	10.69
16-42 in.	45.85	13.62	7.84

The clay is thus in all probability of a siliceous type, as might be expected from its plastic and cohesive character. The relative shallowness of the profile and the absence of concretions suggest a soil in the early stages of development.

The Nipe clay, on the other hand, is an example of a red earth, in which development has proceeded almost to the stage of a ferrallite. It is thus described by Bennett and Allison¹⁴ :—

- 0-26 in. Deep red friable clay with abundance of perdigón (concretions).
- 26-40 in. Red or brownish-red friable clay with less perdigón.
- 40 in.-13 ft. Yellow, exceedingly friable ochreous material.
- 13 ft.-16 ft. Reddish, yellowish, and almost black, exceedingly friable material extending to bed rock.
- 16 ft.+ Serpentine, weathered in upper part, faced along fracture lines with thin coating of bluish to purplish black.

The pH varies about 6.0. The composition of the colloidal clay (G. Edginton) is :—

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃
10.19	15.84	62.51

The highly sesquioxidic character of the clay is reflected in its friable character, whilst its maturity is indicated by the great depth of weathering. The exchangeable bases show the exceedingly low figures of 1.1 milligram equivalents per 100 g. of soil.

The Nipe clay is a highly weathered soil, but it is by no means certain that it represents simply a residual product. The abundant perdigón in the upper horizons certainly represents illuvial material, and it may be that the colloidal clay also is enriched by secondary accumulations of sesquioxides.

Central America. Friable clays of the red earth type are of frequent occurrence in Central America. H. H. Bennett¹⁵ describes a typical profile in the following terms :—

1. Surface layer $1\frac{1}{2}$ to $3\frac{3}{4}$ in. in thickness in which organic matter has slightly darkened the red soil.
2. Red clay uniform to 2-8 feet.
3. Red clay streaked or mottled with material of yellowish, bluish-grey, and whitish or cream colours often mixed with partly decayed rock material.

These soils are devoid of carbonates and low in exchangeable bases. The average silica-sesquioxide ratio for the total soil varies from 0.15 to 1.96.

E. Africa. The writer has been fortunate, through the courtesy of the late Mr. G. Milne, of the Amani Institute, Tanganyika, in securing a number of typical red soils from East Africa. The analytical data obtained from them present many points of interest.

The first profile to be discussed is from Muhesa, Tanganyika. It occurs on the breast of a long slope at about 600 ft. altitude, under a rainfall of about 50 inches per annum. Mr. Milne's description of this profile, which is that of a typical red soil, is as follows :—

“Reddish chocolate top soil, 0.5 inches; red clay below; quartz gravel layer at 30-36 inches; clay again below that, becoming yellow-brown; then yellow to rock-brash and then raw gneiss.”

The analytical data are shown in Table XXXVIII.

TABLE XXXVIII.—ANALYTICAL DATA FOR MUHESA SOIL

Horizon	Clay %	Organic Carbon	pH	Clay Fraction		
				SiO ₂ /Al ₂ O ₃	SiO ₂ /R ₂ O ₃	Al ₂ O ₃ /Fe ₂ O ₃
0-5 in.	55.25	1.65	7.7	2.25	1.64	2.69
12-18 in.	70.94	0.31	6.6	2.23	1.89	5.56

A profile from Kwanishindi, Tanganyika, occurring at 2,700 feet with an annual rainfall of 80 inches, under secondary bush, formerly rain forest, is thus described:—

“Dark coloured chocolate top soil, 0-12 inches; light reddish-chocolate subsoil, cubical structure, much angular quartz gravel; passes through orange and drab-yellow (2 feet thick) to raw gneiss at about 12 feet.”

The analytical data are shown in Table XXXIX.

TABLE XXXIX.—ANALYTICAL DATA FOR KWAMSHINDI SOIL

Horizon	Clay %	Organic Carbon	pH	Clay Fraction		
				SiO ₂ /Al ₂ O ₃	SiO ₂ /R ₂ O ₃	Al ₂ O ₃ /Fe ₂ O ₃
0-12 in.	45.2	3.21	6.3	2.01	1.58	3.68
12-20 in.	45.05	1.89	6.0	1.95	1.53	3.64

Another profile from gneiss near Amani, at 3,300 feet, rainfall 85 inches, in virgin forest is described as

“Dark blackish-brown top soil, 0-8 inches; dark orange-brown subsoil, much rock-brash at 27 inches and below; raw gneiss probably at about 6-8 feet.”

The analytical data are shown in Table XL.

TABLE XL.—ANALYTICAL DATA FOR AMANI SOIL

Horizon	Clay %	Organic Carbon	pH	Clay Fraction		
				SiO ₂ /Al ₂ O ₃	SiO ₂ /R ₂ O ₃	Al ₂ O ₃ /Fe ₂ O ₃
0-8 in.	27.4	6.17	6.1	1.33	0.8	1.51
12-18 in.	40.6	1.72	5.1	1.33	0.78	1.42

An important fact which emerges from these analyses and those of a large number of other soils from East Africa is that larger proportions of organic matter, as judged from the organic carbon, are present than would be thought possible under tropical conditions. The soil from virgin forest at Amani contains over 6% organic carbon, corresponding with about 10-11% of organic matter. Even under secondary bush, the Kwamshindi soil contains the respectable content of 3.21% organic carbon. It should be added, however, that these soils are mainly from fairly high altitudes.

The figures for the composition of the clay fraction in the first two soils do not indicate a pronounced lateritic development. They might be paralleled by many figures for moderately eroded soils in the uplands of Wales. The third example indicates a definitely lateritic type of weathering complex. But even here, the sesquioxidic character is mainly due to the high proportions of ferric oxide.

Southern Nigeria. H. C. Doyne and W. A. Watson²⁶ describe a type of soil to which they give the native name *ilepa*. It is derived from acid igneous rocks under mean temperatures of 70-90°F and a seasonal rainfall of 50-60 in. per annum. The profile consists of the following horizons: (a) brown sandy soil to about 3 ft.; (b) an horizon of concretions, black, orange, and red in colour, sometimes forming a hard pan-like conglomerate; (c) a layer of red clay mixed up with and below the concretions, becoming white-mottled with increasing depth; (d) white clay mottled with red; and (e) rotting rock. The structure of the parent material is recognizable in the clay horizons. The profile is not markedly sesquioxidic. It is considered that the concretions are formed by deposition of hydrated ferric oxide. The surface soil may be adventitious. An interesting feature noticed by Doyne and Watson is the decrease of pH with depth. This has been noted in other tropical soil profiles.

Mauritius. N. Craig and P. Halais¹⁶ give an account of soils derived from doleritic basalt under a mean annual tem-

perature of 23° C and rainfalls varying from 25 to 150 in. per annum. They divide the soils into mature and immature lateritic soils. The mature soils are brownish-yellow, whilst the immature soils are red in colour. The mature soils show a negative correlation between clay content and rainfall. In both classes of soils there is a decrease of the silica/sesquioxide ratio of the clay with rainfall as may be seen from the following mean figures:—

Rainfall in inches	Clay %		SiO ₂ /R ₂ O ₃ of Clay	
	Mature	Immature	Mature	Immature
25-50	73	49	1.68	1.70
50-75	67	53	0.94	1.32
75-100	56	49		
100-125	49	44	0.37	0.65
125-150	45	43		

S.E. United States. Red soils, described in the American system as red podsollic soils, are common throughout the South-Eastern United States and may have affinities with the red soils of the tropics.

A profile near Greensboro, N. Carolina, described by R. C. Jurney¹⁷, showed the following characteristics:—

- A. 0 to 9 in. Slightly reddish-brown clay loam.
- B₁. 9 to 36 in. Deep red heavy brittle clay.
- B₂. 36 to 60 in. Light red friable crumbly clay.
- C. 60 in. + Ochreous yellow, black and reddish-brown decomposed diorite.

There is a marked accumulation of clay in the B₁ horizon. The organic matter decreases from the surface, and the pH falls from 6.3 in the A horizon, to 4.1 in the C horizon. The silica-sesquioxide ratios in the colloidal clay of the successive horizons are 1.46, 1.49, 1.42, and 1.40, respectively. Ferric oxide increases with depth, the figures being 15.71, 18.94, 24.13, and 23.64%, respectively.

L. D. Bayer and G. D. Scarseth¹⁸ have discussed the genesis of red soils in Alabama, with special reference to soils of the Susquehanna series. They consider that the northern limit of the type of weathering characterized by

sesquioxide enrichment corresponds with the 61° F mean annual isotherm.

Western Samoa. F. T. Seelye, L. I. Grange and C. H. Davies¹⁹ describe ferrallitic soils developed under 110-200 in. mean annual rainfall and 78.79°F. mean annual temperature from weathered basalt. In extreme cases they consist almost entirely of hydrated ferric and titanium oxides. They show a "lithomarge" layer over the basalt, enriched by silica washed down from the upper horizons.

Brazil. The Brazilian "*terra roxa*," well known for its fertility, is not, according to F. W. Freise²⁰, a ferrallitic complex. The relative predominance of kaolinitic and ferrallitic weathering depends on the balance between rainfall and evaporation. The descriptions of V. Agafonoff²¹ are in agreement with these views, from which it may be concluded that these soils are of red loam or "younger red earth" character.

Southern China. Red soils in Southern China are described by C. F. Shaw²². They occur under a mean annual rainfall of 50-60 inches. A typical profile under small herbs and grass consisted of 2-5 inches of brownish red clay loam, friable but with very little organic matter, over a clay subsoil of a red colour with reticulate yellow and grey mottling. The parent material is shale and sandstone.

Indo-China. V. Agafonoff²⁰ reports red soils from Indo-China. They are derived from basaltic rocks, and the ferruginous crusts which are developed in certain cases are considered to result from upward translocation of sesquioxides during drought.

FRIABLE AND NON-FRIABLE SOILS

H. H. Bennett¹⁵ had drawn a distinction between friable and non-friable tropical soils. The former appear to belong to Vageler's red earths and Eichinger's older red earths and laterites, and the latter to Vageler's red loams and Eichinger's younger red earths. They are distinguished principally by the character of their weathering complex,

the non-friable soils being relatively siliceous, whilst the friable soils are relatively sesquioxidic in character.

Siliceous and sesquioxidic soils are strongly contrasted in their textural properties. In the former type, the weathering complex is definitely of a clay character and, where present in considerable amounts, gives rise to the characteristic plasticity and cohesiveness of clay soils. In soils whose clay complex contains excess of sesquioxides, the properties of plasticity and cohesiveness are less strongly marked. A soil may contain very high proportions of this weathering complex and yet be of an open friable character.

Comparing friable and non-friable soils in Central America, Bennett obtained the following data (Table XLI).

TABLE XLI. — AVERAGE AND RANGE OF SILICA, FERRIC OXIDE, ALUMINA, TOTAL BASES, AND $\text{SiO}_2/\text{R}_2\text{O}_3$ IN FRIABLE AND NON-FRIABLE SOILS (H. H. BENNETT)

	SiO_2	R_2O_3	$\text{RO} + \text{R}_2\text{O}$	$\text{SiO}_2/\text{R}_2\text{O}_3$
Friable ..	29.30(5.00-41.87)	49.19(31.19-66.72)	1.32(0.13-6.55)	1.25(0.15-1.96)
Non-friable	52.33(41.27-77.00)	39.81(12.18-38.78)	4.50(0.85-17.17)	3.71(2.00-11.60)

The soils of the humid tropics and, indeed, of the humid sub-tropics, appear to present all stages between laterite and soils in which free sesquioxides, even if present, do not dominate the properties of the soil, although their presence may be inferred from the red colours which generally obtain.

AFFINITIES OF TROPICAL RED SOILS WITH BROWN EARTHS

The tropical red soils hitherto described, with the possible exception of the red soils from Southern China, are derived by primary weathering from crystalline rocks. Much of the material on which current ideas of soil classification are based consists of studies on soils of secondary weathering, i.e., in which products of chemical weathering are already present in the parent material. It is therefore important to bear in mind the possibility that some of the

characteristic features of the soils of the humid tropics might be found in soils of primary weathering in temperate climates. Apart from the greater degree of weathering and the occurrence of concretionary material, the writer sees no essential difference between the reddish-brown soils derived from crystalline rocks in Britain and the younger red loams of East Africa. It must be remembered that, even in the humid tropics, concretionary material is not invariably present and, except in ground-water soils, becomes an important constituent only under climatic conditions marked by intense drought.

The more vivid red colours of tropical soils may be attributed to difference in the degree of hydration of the ferric oxide. Whilst, under temperate climates, the hydrates are of the limonitic type, the less hydrated turgite, goethite, and even hæmatite, are probably present in tropical soils.

YELLOW EARTHS

This is a rather ill-defined group of soils of which representatives may occur in the tropics but which is more commonly encountered in sub-tropical and warm temperate climates. The yellow colour is probably connected with a higher degree of hydration of the ferric oxide in these than in the red soils. Yellow earths probably form a transition group between the tropical red soils and the brown forest soils of temperate climates. Certain yellow soils, such as the Norfolk series, in the S.E. United States, are held by C. F. Marbut to differ from adjacent red soils on account of the removal of iron during an earlier stage of impeded or sluggish drainage.

Yellow soils may also result from incipient podsolization of red soils or may represent early stages in the development of red soils. They may also be formed by the weathering of parent materials of low iron content. The use of the term has been discussed by W. Hollstein²⁴. In view of the uncertain position of these soils, it would appear inadvisable

to regard them as constituting a world group. Yellow soils can obviously originate in a variety of ways.

The recognition by the United States Soil Survey of a group known as yellow podsollic soils may provide a convenient repository for the soils hitherto described as yellow earths. If, as in the case of the red loams and red podsollic soils we regard the characteristic colour as belonging to the parent material, we can group together the grey-brown podsollic soils (brown earths), yellow podsollic soils (yellow earths), and red podsollic soils (red loams) as a sequence reflecting the effect of increasing temperature.

LATERITE

In 1807, H. Buchanan²⁵ described a type of red soil occurring frequently in Southern India and proposed for it the name *laterite* (L. later=brick). The term has been widely applied to tropical red soils of widely differing characters and no problem in soil genesis has been more earnestly debated than the nature and mode of origin of this material. The study of tropical soils is, indeed, dominated by the laterite problem. Much of the confusion has arisen through inability to distinguish between soil as a material and soils as individuals. So long as it is thought possible to define a soil by the analysis of a sample, any soil showing a high proportion of sesquioxides may be considered a laterite. Indeed, F. J. Martin and H. C. Doyne¹ proposed to define laterite as a material in which the molecular ratio of silica to alumina in the clay is less than 1.33, whilst in lateritic soils the ratio is 1.35 to 2.0. Apart from the fact that such a definition neglects iron as a constituent of the clay complex, it would have the result of bringing into one group soils of fundamentally different profile characteristics and previous history. The term thus used merely connotes a material. Confusion might be avoided in descriptions of tropical soils if the term *ferrallitic* were substituted for *lateritic* when the intention is merely to convey the information that the

material described is highly sesquioxidic. There are, nevertheless, good reasons for applying the term to certain types of profile occurring in the tropics.

The laterite controversy raises some philosophical problems that may be more appropriately discussed in a later chapter. Much of the confusion has arisen through the assumption, as the writer holds, mistaken, that there is an ideal or universal laterite and that the task of the student of tropical soils is to discover the characteristics or, in the language of the schoolmen, the "accidents" by which it may be recognized. Some have thought to recognize these accidents in the morphology of the profile, some in the chemical composition of the soil material, while some, the most uncritical, have even thought to recognize laterites in tropical soils with red colours. If the term laterite is to be used in pedology, it would probably be safest to adopt a frankly empirical position and propose that the term shall be restricted to one alone of the many types of soil actually occurring in the tropics.

On grounds of practical convenience, the ideas of R. L. Pendleton²⁷ may be commended. This writer would restrict the use of the term laterite to profiles characterized by the presence of concretionary material or crusts overlying mottled or vesicular horizons, and presumably developed under ground-water influence as first described by J. M. Campbell²⁸ in W. Australia and Africa. The application of the term would thus be denied to ferrallitic material of primary weathering such as the Nipe Clay of Cuba and similar soils developed from ferrallitic materials under conditions of free drainage. Pendleton follows Campbell in considering laterites to have been developed originally as psuedo-illuvial deposits in the zone of a fluctuating water-table under peneplanic conditions. On later uplift and dissection, the ground-water conditions disappeared and a new direction of profile development was induced. Profiles whose characteristics may be explained on this hypothesis occur in many parts of the world.

The description of a typical laterite profile as given by H. Harrassowitz^b exhibits some of the principal features of this soil group. According to this writer, the profile consists essentially of four horizons, namely, (1) the parent rock, succeeded by (2) an horizon representing the material of primary weathering, which appears to be of a kaolinitic character in turn succeeded by (3) the lateritic horizons, passing into (4) a surface horizon characterized by ferruginous incrustations or concretions. The zone of decomposition may be a mere film or may attain a thickness of a metre or more.

Harrassowitz's lateritic horizon consists of red material mottled with yellow or even violet, generally argillaceous, but when derived from quartzose rocks, often sandy in texture, it has a tendency to a vesicular or cellular structure and the pores are frequently fitted with white or greyish material. When moist, it may be dug out, but hardens on drying so that it may be used as a building material. The surface ferruginous crust may attain such a development as to preclude the growth of vegetation. With it is associated free alumina as gibbsite or hydrargillite.

C. G. Stephens²⁹ has studied pedogenesis following laterite formation in Southern Australia. Adopting Campbell's views as to their original formation he considers these laterites to have been developed during Tertiary times. More recently, uplift, dissection and new profile development have taken place. He describes normal and truncated profiles and considers the normal profile, developed from the original laterite, as essentially podsolic. The characteristic features surviving from the original laterite formation are (1) the horizon of nodular or pisolitic laterite gravel, underlain by (2) clay with mottled yellow, red and yellowish grey colours. The superficial bleached sandy horizons are presumably of later and roughly contemporary origin.

R. L. Pendleton (*loc. cit.*) has described laterites in Siam, where they are widely developed. He follows Campbell in considering them to be ground-water formations

and distinguishes two processes, namely (1) those occurring in deep horizons where the geological parent rocks are permanently saturated with water; in this zone, iron compounds go into solution; and (2) those occurring above this zone, where ferrous compounds become oxidized through access of air. This oxidation takes place in the moist pore-spaces above the water-table giving the characteristic mottled appearance of the laterite horizon. R. L. Pendleton and S. Sharastuvana³⁰ give numerous analyses of lateritic profiles from which it appears that the concretionary material, whilst generally sesquioxidic in character, may contain considerable proportions of silica. The presence of superficial bleached horizons has been noted in many lateritic profiles, which some authors have described as podsolized. Pendleton considers that such bleaching differs entirely from podsolization, which occurs in the presence of raw humus, and is more properly termed *lixiviation* following the usage of E. C. Mohr.

Whilst the typical lateritic profile would appear to be marked by the presence of an horizon of concretionary or crust-like material underlain by mottled clay, there are also profiles in which, although concretionary material occurs, the mottled horizons are absent. Such a type is described by F. Hardy and R. R. Follett-Smith³¹. It occurs in British Guiana and is derived from hornblende-schist. Their description is as follows:—

1. Superficial laterite and ironstone, frequently vesicular and slaggy, scattered in blocks on the surface.
2. Topsoil. Red-brown humic clay, 9 inches.
3. Tawny red earth, friable and very gravelly, especially in its upper part. The gravel consists of pieces of laterite, ironstone pellets, and quartz fragments. Thickness 10-20 feet.
4. Primary red laterite, hard and crusty. Thickness 3 inches over broken rock surface.

Gibbsite ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$) occurs throughout the profile. It would appear that in this type of profile a ferrallitic material is the primary product of weathering. F. J. Martin and H. C. Doyne²⁶ also have recorded the direct formation of similar material from norite in Sierra Leone.

The parent material appears to have considerable significance, for, according to Hardy and Follett-Smith, acidic rocks such as granite do not yield laterites. This may be connected with the formation of a kaolinitic type of weathering product from the potash and potash-soda feldspars occurring in such rocks. It will be remembered that the non-sesquioxidic "ilepa" soil of S. Nigeria, described by Doyne and Watson²⁶ (p. 404) is derived from acidic rocks.

Great differences of opinion exist as to the mechanism of laterite formation. It is considered by J. B. Harrison² that two main processes may be distinguished, namely, (1) primary lateritic formation and (2) re-silicification of the lateritic product by deposition of silica from ascending solutions. The latter process only takes place in localities affected by a high water-table. Otherwise, the laterite appears to be permanent.

F. Hardy and R. R. Follett-Smith (*loc. cit.*) adduce evidence for a process similar to podsolization affecting the upper horizons of lateritic profiles, whereby sesquioxides are removed by leaching.

J. M. Campbell²⁸, from a study of Australian and African laterites, considered laterites to result from changes which occur in the zones of permanent and intermittent saturation in the vicinity of a water-table. Since oxygen is necessary for the oxidation of ferrous to ferric iron, the proximity of these zones to the surface is a further condition for its formation.

The hydrated sesquioxides deposited in the lateritic horizons originate by hydrolysis of silicate minerals and occur in the ground-water in alkaline solution, the iron as ferrous hydrogen carbonate and the aluminium as alkaline aluminates. During periods of drought, there is an upward translocation of dissolved material from the water-table. Ferrous hydrogen carbonate undergoes oxidation, giving amorphous hydrated ferric oxide, whilst the aluminates give rise to amorphous hydrargillite $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$.

Subsequent changes in the lateritic horizon involve the formation of turgite $2\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$ and possibly hæmatite,

Fe_2O_3 , from amorphous ferric oxide hydrate, and crystalline gibbsite $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ from hydrargillite. On account of the greater mobility of ferric oxide in colloidal solution, it may happen that lateritic horizons become progressively more aluminous in character with age.

The views of Campbell are supported by the investigations of W. G. Woolnough²² in Western Australia. This author considers that laterization can occur only in situations in which free drainage is at a standstill, as in a peneplain at or about sea level. High level laterites are products of processes which have long since ceased consequent on uplift and the alteration of hydrological conditions. Laterite, as imagined by these authors, was formed by a process which may be paralleled by the formation of "murrum" and "mocarrero" in contemporary vlei soils. Lateritic soils may, indeed, be considered as the tropical analogues of the gley soils of temperate regions.

The formation of a material such as the Nipe clay, which appears to be mainly residual in character, must obviously be distinguished from the processes whereby profiles characterized by slaggy ferruginous incrustations are developed. In these, the more typical lateritic profiles, it is clear that there has been a deposition which has masked the primary processes of silicate hydrolysis and clay formation. It cannot be assumed in all cases, however, that profile development has been influenced by the proximity of ground-water, for contemporary laterites may occur under savannah. An alternation of extreme wetness followed by desiccation may have the same effect as a fluctuating water-table.

Whether or not illuvial deposition of sesquioxidic material has taken place in the presence or absence of a high ground-water table, it is evident that the principal climatic circumstances are high temperature and the alternation of aerobic and anaerobic conditions within the soil profile.

The mobility of sesquioxidic constituents in the soil profile has been attributed by Campbell to the alkalinity of the ground-water, by H. Harrassowitz⁸ to the protective effect

of humus sols and by A. Reifenberg³³ to the protective effect of silicic acid sols. It is probable that each of the three explanations may find an application in the wide range of lateritic profiles encountered.

VOLCANIC SOILS

This somewhat misleading name is given to soils derived from volcanic ashes and tuffs under tropical and sub-tropical conditions. The nature of the parent material is such that it weathers very rapidly. F. Hardy³⁴ reports that andesitic ashes, accumulated during the eruptions at St. Vincent, B.W.I., in 1902-3, were able to carry agricultural crops within one year with the aid of small organic dressings. Similar instances of the rapidity with which such materials become available for agricultural use can be found in many parts of the world. The character of the ash is of importance. Whilst highly acid ashes weather slowly, basic ashes weather rapidly to fertile soils. N. H. Taylor³⁵ reports volcanic ash soils from New Zealand of an aluminous character.

GENERAL CONSIDERATIONS ON TROPICAL SOILS

Some of the general characteristics of tropical soils were mentioned at the beginning of this chapter. Many of these distinctive features might be regarded as geological rather than as pedological. The occurrence of highly weathered parent materials, often markedly ferrallitic in character, and the extensive erosion and re-sorting of the superficial deposits that has taken place are all distinct from the processes of pedogenesis, if by this term is understood the development of the profile. On the other hand the characteristic but little understood organic matter regime, the eluvial processes, and the tendency to concretionary developments in the profile are essentially connected with pedogenesis.

In spite of these marked peculiarities of tropical soil formation the affinities of tropical soils with those of temperate regions must not be overlooked. The tropical red loams can be regarded as the analogues of the temperate brown earths, the tropical laterites of the temperate gley

soils, and the bleached surface layers sometimes encountered betoken a process akin to podsolization.

The problems that confront the pedologist in the tropics are as much geological as pedological. How closely geology and pedology are associated in producing the tropical soil pattern may be readily seen from a perusal of the late Geoffrey Milne's¹⁶ *Soil Reconnaissance Journey through Parts of Tanganyika Territory*. Unfortunately, the geologist is mainly concerned with the solid geology, and the necessary interpretation of regolithic phenomena must be the responsibility of the pedologist.

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CHAPTER XV

SOILS ASSOCIATED WITH CALCAREOUS PARENT MATERIALS

THE soils to be discussed in the present chapter are grouped together principally for descriptive purposes and not, necessarily, because they form a major group in a world system. Their position in such a system will be discussed at a later stage.

Soils derived from or associated with calcareous parent materials, such as limestone, chalk, or coral, appear to fall into two main groups. On the one hand, is a group of soils in which the mineral colour is grey or greyish-brown, and the colour of the soil as a whole tends towards brownish or greyish-black shades. With them may be grouped white or grey chalk soils in which the organic matter colour is masked by the excess of chalk. On the other hand is a group of soils in which the colour is predominantly red or reddish-brown, sometimes modified by the presence of organic matter, which would appear to be of a different character from the organic matter of the soils of the first group. The clay complex of the black and grey soils is more siliceous than that of the red and brown soils, which appears to contain free sesquioxides. Soils of the first group contain free calcium carbonate and are completely saturated with exchangeable bases, whilst soils of the second group generally show a distinctly lower base-status and may be actually acid in reaction. To the first group belong the *rendzinas*, with which may be included the grey and white limestone soils of the temperate regions, and the black limestone and marl soils of the tropics. To the second group

belong the so-called *terra rossa* soils, with which may be included the brown and red limestone soils of temperate regions and the red limestone soils of the tropics.

RENDZINAS AND RELATED SOILS

These soils have been most widely studied in Central Europe. They are sometimes described as humus-carbonate soils. They are, typically, dark coloured soils containing from 3-12% of organic matter and varying amounts of free calcium carbonate. In Glinka's system of classification, they are considered to be typical endodynamomorphic soils, which have not yet reached mature development and in which the profile character is mainly determined by the nature of the parent material. Though generally of a dark colour, soils belonging essentially to this class may also be dull brown or even grey in colour. Reddish-brown colours do not occur.

W. Kubiena¹ distinguishes "proto-rendzinas" and "mull rendzinas," the former being of a skeletal type without earthworms and the latter having well developed mull with abundant earthworms.

According to K. D. Glinka² the essential features of a rendzina profile are :—

- A₁. Grey, dark grey, or almost black soil, sometimes containing fragments of chalk or marl. Thickness 15-30 cm.
- A₂. Whitish-grey, slightly humus coloured or brownish, with more fragmental chalk or marl than in the A₁ horizon.
- C. Calcareous parent rock.

L. G. Kotzmann³ gives the following as the typical features of a Central European rendzina profile developed on pure limestone or dolomite :—

- A. Dark grey or almost black soil with loose crumbly structure. Different-sized fragments of limestone or dolomite, sometimes coloured with iron, soil generally sharply delimited from the parent rock, free of humus and contamination. Thickness varies from 20 to 30 cms. Organic matter content up to 20-25%.
- C. Upper part of parent rock generally consists of pink-coloured fragments increasing in size with depth (C₁). Below it is unaltered limestone or dolomite.

The clay fraction is generally carbonate-free and appears to consist mainly of quartz and the weathering complex, which is of a siliceous character.

Poland. S. Miklaszewski⁴ distinguishes two groups of rendzinas, namely, those derived from calcareous parent materials and those from gypseous parent materials. Among the calcareous rendzinas, white, brown, and black varieties occur. The colour is not always correlated with humus content, for an instance is given of a white rendzina, containing 3.5% of humus, adjacent to a black rendzina with 2.8% of humus. The white rendzinas are probably similar to the white chalk soils of England, in which the organic matter colour is masked by the excess of chalk. The presence of considerable proportions of calcium carbonate is a constant feature of typical rendzinas.

England. There is now fairly general agreement in assigning the chalk soils of England to the rendzina group. The prevalence of grey or brownish-grey colours and the presence of free calcium carbonate would appear to warrant their inclusion. Even in the light-coloured chalk soils, the residue after removal of calcium carbonate has the dull greyish-black colour characteristic of organic matter formed in the presence of excess of calcium carbonate.

The chalk soils of Great Britain generally appear to have undergone considerable erosion, and this has tended to obscure their relationship to the continental rendzinas. Yet, under certain conditions, profiles occur in which there is a well marked greyish-brown or even black surface horizon.

A chalk soil profile, occurring under arable cultivation near Wantage, Berkshire, is described by Miss F. F. Kay⁵ in the following terms:—

- 0.10 in. Grey fine sandy silt clay loam; very calcareous, loose.
- 10-16 in. Putty-coloured fine sandy silt loam containing many fragments of chalk rock, which increase in size with depth.
- >16 in. Chalk (Lower Chalk) rock.

The following analytical data were obtained on samples of the above profile (Table XLII).

TABLE XLII.—ANALYTICAL DATA FOR WANTAGE SOIL PROFILE

Horizon	CaCO ₃ %	Organic Carbon %	Clay Fraction		
			SiO ₂ /Al ₂ O ₃	SiO ₂ /R ₂ O ₃	Al ₂ O ₃ /Fe ₂ O ₃
0-10 in.	21.0	2.2	5.65	4.47	3.79
10-16 in.	36.1	0.65	5.95	4.63	3.51

The same writer gives the following description of a dark-coloured rendzina under old pasture on the downs near Newbury :—

- 0-5 in. Dark brown organic friable loam (turf layer); crumb structure, loose.
- 5-7 in. Layer of medium sized sub-angular flints.
- >7 in. Brown stained chalk fragments and flints passing into unbroken chalk (Upper Chalk) rock.

The following analytical data were obtained for the top layer :—

CaCO ₃ %	Organic Carbon %	Clay Fraction		
		SiO ₂ /Al ₂ O ₃	SiO ₂ /R ₂ O ₃	Al ₂ O ₃ /Fe ₂ O ₃
1.45	9.6	3.16	2.47	3.58

The clay fraction is less siliceous than in the Wantage soil, probably reflecting the differing character of the parent chalk.

Wales. Certain soils derived from the Lower Lias would appear to belong to the rendzina group. The following is a description by D. O. Hughes^b of a typical profile in Glamorganshire under old pasture :—

- 0 to 6 in. Greyish-brown stoneless clay loam.
- 6 to 15 in. Light yellowish-brown clay, with occasional fragments of limestone.
- >15 in. Soft limestone.

The following analytical data were obtained (Table XLIII).

TABLE XLIII.—ANALYTICAL DATA FOR LIAS SOIL PROFILE

Horizon	Clay	CaCO ₃	Organic Carbon	Clay Fraction		
				SiO ₂ /Al ₂ O ₃	SiO ₂ /R ₂ O ₃	Al ₂ O ₃ /Fe ₂ O ₃
0-6 in.	39.5	2.7	3.3	4.50	3.56	3.79
6-15 in.	44.0	17.7	1.2	4.29	3.47	4.24

The highly siliceous character of the clay fraction is a distinctive feature of soils belonging to this group which have been examined by the writer. On theoretical grounds, the same character may be expected in all soils containing an excess of calcium carbonate, maintaining a state of base-saturation.

The writer has encountered a dark-coloured pasture soil over Carboniferous Limestone near Penmon, Anglesey, consisting of 5 inches of black crumbly humous loam with abundant limestone fragments over shattered limestone.

Cuba. The Camaguey series of Cuba described by H. H. Bennett and R. V. Allison⁷ may serve as an example of a tropical black limestone soil. Typically it consists of (1) 6-14 in. of dark brown to black clay, overlying (2) dark brown to yellowish-brown plastic clay, frequently calcareous, grading at 20-30 in. into (3) brownish-yellow to yellow, plastic and somewhat sticky clay, frequently calcareous and containing lumps of soft calcium carbonate, overlying at 40-72 in. (4) either whitish cocó (chalky limestone), pale yellow calcareous clay and white cocó, or cocó and calcareous clay, interbedded with hard or semi-hard limestone.

The analytical figures given show that calcium carbonate is present throughout the profile. The organic matter in the surface soil is 9.62%.

Barbados. S. J. Saint⁸ describes black soils derived

from coral limestone, which appear to be of the rendzina type. The following is typical.

0-12 in. Black surface soil.

12-24 in. Black subsoil with greyish-white streaks.

24-36 in. Greyish-white soapy clay; black streaks and concretions.

The analytical figures are as follows:—

TABLE XLIV.—ANALYTICAL DATA FOR BARBADOS BLACK LIMESTONE SOIL

Horizon	Mg.C	CaCO ₃	Clay	Clay SiO ₂ /R ₂ O ₃
0-12 in.	1.09	4.8	60.7	3.34
12-24 in.	0.67	3.7	68.6	3.36
24-36 in.	0.58	5.8	73.0	3.14

MAGNESIUM RENDZINAS

V. Novák and J. Pelišek⁹ describe soils derived from serpentine in Moravia which appear to be related to the rendzinas. They are alkaline to the surface and have a very stable structure. The parent rock contains only a trace of calcium, but has 38.6% MgO. This is reflected in the character of the exchange complex in which about 80% of the exchangeable cations are represented by magnesium. They are thus definitely magnesium soils in contrast to ordinary rendzinas, which are calcium soils. Novák and Pelišek term them *magnesium rendzinas*.

RED AND BROWN LIMESTONE SOILS

Terra rossa is the name given to a red soil which occurs commonly in the countries bordering on the Mediterranean Sea. Typically it is associated with limestone and in the present account we shall follow the definition of A. Reichenberg¹⁰ in restricting the term terra rossa to such soils.

The soils included in this group show a simple type of profile consisting of a variable depth of red soil sometimes slightly modified in colour by admixture of humus in the upper horizon, and passing abruptly to the limestone rock below without any marked zone of transition. Typically, the terra rossa soils are fairly heavy clays. Analyses by W. Graf zu Leiningen¹¹ show clay contents varying from

32.85 to 59.05% in typical examples. The coarser fractions are correspondingly small. In some cases, fragments of the parent rock and also calcareous concretions stained red with iron oxides are present.

Although numerous bulk analyses are found in the literature, scarcely any data are available for the composition of the clay fraction. A clay from Pikermi examined by zu Leiningen gave a clay fraction having the composition,

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Ignition
41.62	21.16	12.85	3.82	15.05

Similar figures were obtained by E. Blanck, F. Kunz, and F. Preiss¹² for certain red soils from Moravia with resemblances to terra rossa. The present writer has made partial analyses of the clay fractions of two red soils over limestone from Cap d'Antibes, S. France, and St. Gowans Head, Pembroke-shire, respectively. The figures are as follows:—

		SiO ₂ /Al ₂ O ₃	SiO ₂ /R ₂ O ₃	Al ₂ O ₃ /Fe ₂ O ₃
Cap d'Antibes	...	2.61	2.04	3.19
St. Gowans Head		2.51	1.95	3.51

Neither the abundant data for the bulk composition of terra rossa soils nor the few available data for the composition of the clay fraction suggest any tendency towards ferrallitization. The figures are such as might be obtained from typical brown earths, or younger red tropical loams.

Generally speaking, terra rossa soils are base-unsaturated. Calcium carbonate is, indeed, shown in certain analyses, but it is not improbable that it may be present in the form of fragments which, by reason of their size or degree of induration, are without effect on the base-status of the body of the soil. In this connexion, it has been remarked by K. D. Glinka, that whilst soft limestones produce rendzina soils, hard limestones produce red soils. If the development of red soils be a consequence of a lowering of base-status, it is readily seen that such a process can most readily take place in soils derived from hard limestones.

The problem of the origin of terra rossa has been

earnestly debated both by pedologists and geologists. The theory that it is simply a residual product from the parent limestone is inadequate, since material resembling terra rossa cannot be obtained by dissolving away the carbonates from limestones. And, therefore, whilst its close association with the limestone suggests an origin from the non-carbonate portion of the rock, it is evidently necessary to account for the changes whereby this material has become terra rossa.

H. Stremme¹³ considers terra rossa to be analogous to the B horizon of podsol profiles, the A horizon having been removed by erosion. But whilst red subsoils similar to terra rossa occur in certain parts of Central Europe under humus surface soils, it does not appear possible to apply this theory of their origin in the Mediterranean region generally.

A. Reifenberg⁷, from an intensive study of the conditions of terra rossa formation, concludes that the essential feature in its formation is the irreversible precipitation, in the surface horizons, of sesquioxide sols peptized by silicic acid. Such data as are available, however, do not suggest a high content of sesquioxides for terra rossa, and it may be more correct to regard these soils as analogous to the brown earths, in which, if we accept the views of A. Stebutt, the lowering of the base-status has resulted in a partial degradation of the zeolitic or clay complex into its component silicic acid and sesquioxides.

A full discussion of the problem of terra rossa is given in Blanck's *Handbuch der Bodenlehre*, Vol. III. (pp. 193-257). A more recent discussion is given by W. Hollstein¹⁴. Perhaps the most baffling problem is that of the origin of the iron oxide. It has been remarked that the best developed terra rossa soils are on the purest limestones, and it may well be that the iron is of external origin, possibly from volcanic dust. A relationship with the red clay of the greater oceanic depths would be worth investigation.

Cuba. As an example of a tropical red limestone soil, the Matanzas series of Cuba described by H. H. Bennett and R. V. Allison¹⁵ may be cited.

The profile is comparatively simple and consists of a uniform red friable clay, which may reach to 15 feet or more with an abrupt transition to the parent rock. The top 3-6 inches is somewhat darker in colour through the presence of organic matter. A characteristic of this series is the occurrence of concretionary material (perdigón). The parent rock is light coloured limestone, locally flinty, or limestone and cocó.

The analytical figures presented show a complete leaching of calcium carbonate, a condition which is reflected in the acid reaction of the soils of this series. The organic matter content in the three surface soils for which data are given varies from 2.19 to 4.65%. Although no data for the composition of the clay fraction are available, free sesquioxides are probably present. The concretions consist mainly of ferric oxide with smaller proportions of alumina and silica.

United States. The Hagerstown series which is found in the Blue Ridge region of the United States belongs to the group of red and brown limestone soils. The soil profile, where mature, consists of a light-textured light brown A horizon and a brown or reddish-brown B horizon. Calcium carbonate has been entirely removed from the profile by leaching. Another example of this group is the Decatur series of Georgia and neighbouring states.

Wales. Brown, red, and reddish-brown soils are commonly found on hard Carboniferous Limestone in Wales under conditions which have resulted in decalcification and desaturation. It is noteworthy that, under the same climate, the soft Lias Limestone gives rise to greyish-brown soils. The following profile is found on Carboniferous Limestone at Bridgend, Glamorgan:—

- 0-9 in. Rusty reddish-brown silty heavy loam.
- 9-15 in. Brown silty heavy loam with fragments of limestone.
- >15 in. Hard limestone.

Fragments of limestone occur in both horizons and markedly in the second horizon. Yet the soil is partly leached, for the pH is 5.96 and the exchangeable lime

figures, 0.379% and 0.313% respectively for the two horizons, indicate partial desaturation. The composition of the clay fractions is as follows:—

	$\text{SiO}_2/\text{Al}_2\text{O}_3$	$\text{SiO}_2/\text{R}_2\text{O}_3$	$\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$
0-9 in.	2.50	2.07	4.81
9-15 in.	2.76	2.17	3.67

These figures show a marked contrast with those for neighbouring greyish-brown Lias soils, which appear to belong to the rendzina group.

Whilst in ordinary Welsh profiles, the tendency is for sesquioxides to increase in the clay fraction from the surface downwards, there is here no evidence of eluviation in either direction. The $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$ ratio decreases with depth.

The fairly high proportions of organic matter in the desaturated limestone soils of Wales tend to mask their mineral colour, which is often decidedly brick-red. More commonly the colour is a warm reddish-brown.

RELATIONSHIP OF RENDZINAS TO RED AND BROWN LIMESTONE SOILS

We have seen that limestones can give rise to two distinct groups of soils. The one group is characterized by a high base-status, excess of calcium carbonate, a dark coloured type of organic matter, and a grey or greyish-brown mineral colour associated with a siliceous type of clay, probably devoid of free sesquioxides.

The other group is characterized by a generally low base-status, sometimes even in the presence of fragmentary limestone, a type of organic matter of a lighter colour than that of the first group, and a red or reddish-brown mineral colour, associated with a type of clay having a $\text{SiO}_2/\text{R}_2\text{O}_3$ ratio of about 2.0 or less, in which there is a certain proportion of free sesquioxides.

The formation of the second group appears to follow the desaturation of the soil, and we may therefore regard the red limestone soils as more mature than the grey or rendzina

soils. In a limestone country, it should be possible to discern different stages of maturity due to variations in topography. If mature leached soils are to be found, they may be expected in upland situations with relatively high rainfall and intense leaching, provided erosion is not severe enough to keep pace with profile development.

An example of this is furnished by red and black soils derived from coral limestone in Barbados, described by S. J. Saint⁸. The red soils occur in the districts of highest altitude and greatest rainfall, whilst the black soils occur in the drier lowlands. All intermediate gradations are found between the extremes. The black soils are more colloidal than the red soils, and have a more siliceous clay fraction. Thus, the clay $\text{SiO}_2/\text{R}_2\text{O}_3$ ratio for the upland red soils is 1.95, whilst the corresponding figure for the lowland black soils is 3.29. It is rather remarkable that the red soils have a higher organic matter content than the black soils. The dark colour of the latter soils may be associated with the higher calcium status of the humus, a circumstance which has been remarked elsewhere; but Saint considers it to be of mineral origin. According to Saint, the key to the distinction between the two types lies in the greater maturity of development of the red soils.

J. M. Albareda and E. Gutiérrez Ríos¹⁶, from a study of soils derived from limestone in Spain, conclude that the Spanish red soils, which may be regarded as belonging to the terra rossa class, have been formed by the degradation of rendzinas consequent on deforestation under semi-arid conditions. Under forest the tendency of evolution would be towards brown earth or podsollic types.

In the writer's experience, soils derived from hard limestones in Wales under conditions of intense leaching always show reddish or brownish colours, whilst colluvial soils or soils in situations with imperfect drainage are generally greyish or brownish-grey. Some figures recently obtained for an Anglesey profile in limestone drift support the view that desilicification accompanies decalcification. The soil

down to 30 inches is devoid of calcium carbonate and the clay $\text{SiO}_2/\text{R}_2\text{O}_3$ ratio is 1.85 for each 15-inch layer. Below 30 inches the material is calcareous and has a clay $\text{SiO}_2/\text{R}_2\text{O}_3$ ratio of 3.90.

In view of these considerations, it may be permissible to hazard a conjecture that the red Clay-with-flints overlying certain parts of the Chalk of S.E. England may represent a mature limestone soil. Against the view that it is a residual product from chalk it has been urged that the chalk which has been weathered away could not have produced a layer of Clay-with-flints of the thickness which actually occurs. Yet a considerable proportion of the clay must be chalk residual material, and it is not impossible that some additions may have been made by illuvial accumulation as has been suggested for the terra rossa.

It may be remarked that mature limestone soils tend to resemble the soils of warmer climates. The Mediterranean terra rossa shows points of resemblance with the red loams of the tropics, whilst the red colours of leached limestone soils of more northern climates are in marked contrast to the more sober brown colour of adjacent soils derived from non-calcareous parent materials. This may be attributed to the drier and, therefore, warmer character of these soils and to the more rapid mineralization of plant residues.

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CHAPTER XVI

THE CLASSIFICATION OF SOILS

INTRODUCTORY

ATTEMPTS to classify soils have been made from the earliest days, and in this matter the practical man has preceded the scientist. Farmers from the earliest times have recognized different kinds of soil through hard experience and have given them names usually expressing their differing textures. In modern times the connexion between soil and parent material was soon recognized, and one of the earliest attempts to find a scientific basis for classification was that of F. A. Fallou¹, who, from his experience in Saxony, proposed a petrographical-geological system. This and most of the earlier essays in classification suffered from their limited geographical scope and from their inadequate knowledge of the different factors, such as climate and topography, operative in soil development. The significance of the soil profile has been generally recognized only within comparatively recent years.

Before entering on a detailed consideration of the different systems of soil classification, it may be helpful to examine some of the philosophical problems involved, in order to understand the general limitations inherent in all attempts to group soils into ordered systems.

If we wish to describe the soils of a farm, of a parish, of a country, or indeed of the whole world, some kind of a classification or ordered arrangement is necessary. In classifying soils, as in classifying any other objects, many distinct methods are conceivable. For example, we might classify soils according to their colour, their organic matter content, their texture, and so on, and each of these classifi-

cations might have a certain value. We may distinguish two contrasted approaches to the problem. On the one hand, we may base our classification of soils on the various factors that have contributed to their formation, such as parent material, climate, and topography; on the other hand we may make our classifications in terms of observable soil properties. The first type of classification is exemplified by petrographical, climatic, and vegetational classifications, the second by classifications based on profile characteristics. If we use the term "property" in its widest sense to include not only observable characters but also the factors known or supposed to have been operative in forming the soil, we might define a class X in a particular system as being a number of soils having properties A, B, C, D, etc., in common. A classification giving classes, in which all members of each class have all properties in common, is impracticable with such a variable object as the soil. And therefore, within a class of soils, there must always be a number of properties in which differences are shown. The problem consists in the selection, perhaps not exhaustive, of properties common possession of which shall define the class. Here it is necessary to distinguish properties according to their significance and in this connexion it is relevant to quote some remarks of J. S. Mill (*System of Logic*, 1879, Vol. II., pp. 270, 272) on the subject of classification:—

"Classification, thus regarded, is a contrivance for the best possible ordering of the ideas of objects in our minds; for causing the ideas to accompany or succeed one another in such a way as shall give us the greatest command over our knowledge already acquired, and lead most directly to the acquisition of more."

"The ends of scientific classification are best answered, when the objects are formed into groups respecting which a greater number of general propositions can be made, and those propositions more important, than could be made respecting any other groups into which the same things could be distributed. The properties, therefore, according to which objects are classified, should, if possible, be those which are causes of many other properties, or, at any rate, which are sure marks of them. Causes are preferable, both as being the surest and most direct of marks, and as being themselves the properties on which it is of most use that our attention should be strongly fixed. But the property which is the cause of the chief peculiarities of a class is unfortunately seldom fitted to serve also as the diagnostic of the class.

Instead of the cause, we must generally select some of its more prominent effects, which may serve as marks of the other effects and of the cause."

The selection of the properties for use as criteria in classification is not always easy, for their significance may not be plainly apparent. Thus, mechanical composition may appear very significant because of its importance in practice, yet the grouping of soils into classes with similar or identical mechanical composition would bring together soils that would differ from each other in most important respects. The aims of a practical classification and those of a scientific classification may run counter to each other. Thus, for certain practical purposes we may group together soils that are widely different from the scientific standpoint, just as the term "roots" in crop husbandry includes crops belonging to the Cruciferae, Chenopodiaceae, and Solanaceae—widely separated natural orders.

Contrasted with classifications based on the observable properties of soils, there are those based on external circumstances or factors that have contributed to soil formation. Many classifications based on soil-forming factors have been proposed and all have a certain value. Strictly speaking, these are not classifications of soils but of the factors concerned in the formation of soils. H. Jenny (*Factors of Soil Formation*), indeed, prefers to express the known variations in soils by a series of equations expressing the effect of different factors on soil properties. Such an approach to the problem would dispense with the recognition of definite classes and arrange soils in sequences. (Cf. p. 458.)

Jenny criticizes the whole idea of grouping soils into classes and prefers to characterize soils by functional relationships based on equations showing individual soil properties as functions of the different pedogenic factors. Speaking of soil maps he remarks ("Factors of Soil Formation," p. 262):—

"The goal of the soil geographer is the assemblage of soil knowledge in the form of a map. In contrast, the goal of the 'func-

tionalist' is the assemblage of soil knowledge in the form of a curve or an equation. These objectives are clearly brought out in a comparison between Marbut's *Soils of the United States* and the present treatise on soil-forming factors. The former abounds with carefully executed maps of various scales, whereas the latter displays a sequence of graphs and equations. Both methods of approach have their merits, and nothing would be gained by playing one system against the other. Soil maps display the areal arrangement of soil properties and types but give no insight into 'causal' relationships. The curve, on the other hand, reveals the dependency of soil properties on soil-forming factors, but the conversion of such fundamental knowledge to specific field conditions is impossible unless the areal distribution of the soil formers is known. Clearly, it is the union of the geographic and the functional method that provides the most effective means of pedological research."

If we accept these ideas, the boundaries shown on a soil map are largely arbitrary and merely mark the occurrence of conventional points on a series of continuous curves. Yet we cannot entirely abandon the idea of soil boundaries or the possibility of representing soils cartographically. Whilst successions such as chernozem to desert or podsol to brown earth may be so gradual as to preclude definite boundaries, in other cases definite boundaries plainly exist. A change in parent material often results in a perfectly definite and mappable boundary, as may be seen over many parts of Britain. Similarly, topography may result in a sharp transition from soils of free drainage to soils of impeded drainage. The practical soil surveyor, although aware of the occurrence of transitional soils and merging boundaries, cannot but be aware of the existence of definite and mappable soil classes. It is, however, necessary to regard soil maps critically and to distinguish between soil boundaries of objective significance and those based on a subjective interpretation of the field data. We should also recognize another way in which soil maps fail to correspond exactly with the physical facts, namely, where generalized boundaries have been drawn in regions of great cartographic complexity. A soil map at best is only an approximate picture.

The problems of soil classification illustrate and are illustrated by the important philosophical problem of

*universals** and a short digression on this problem may be helpful to the student of soil.

If we consider any common object such as chair or table, it is clear that it is known to us only through sense-perceptions such as hardness, colour, shape, and so on. This led Plato to his theory of ideal forms. A particular table is merely a manifestation to our sense of an ideal table. We need not follow Plato into his world of ideals, which has in it, perhaps, as much of poetry as of philosophy. The Platonic ideas formed the basis of early medieval scholasticism which, following St. Augustine, accepted the belief in ideal forms or, as we should now say, universals, existing independently of their material manifestations. Whether it was possible to know these forms directly was a matter for controversy. This extreme position known as Augustinian Realism was modified as the ideas of Aristotle permeated western thought, at first through Boethius and later through the Arabian philosophers. In its later form as developed by St. Thomas Aquinas, universals were considered as existing not antecedent to, but in the objects to which they referred.† Against Realism was the opposite doctrine of Nominalism, according to which universals are merely names and not independent facts. The issue was raised by Boethius in a commentary on Porphyry when he enquires whether genera and species exist in the same way as objects perceived by the senses. Are they not rather the products of our own thought and without counterpart in the real world? Intermediate between Nominalism and Aristotelian-Thomist Realism is Conceptualism which, whilst denying universals, admits the possibility of concepts, framed arbitrarily by the mind by abstraction from particular impressions.

*The following works have been found helpful in furnishing the ideas underlying this discussion. Bertrand Russell, *Problems of Philosophy* and *History of Western Philosophy*; M. H. Carré, *Realists and Nominalists*; J. Maritain, *Introduction to Philosophy*. In preparing this discussion I have been helped by discussion with my friend Professor R. I. Aaron, who does not necessarily subscribe to the views expressed therein.

†According to St. Thomas, the abstraction of the universal (*species intelligibilis*) from the concrete particulars is the result of the operation of the active understanding (*intellectus agens*)

These old controversies become alive if we apply them to our thoughts about classes or kinds of soil. Has the "idea" of podsol an existence independent of our minds or does it merely mean a name applied to a range of soil profiles which, from our limited acquaintance with them, we believe to have enough in common to warrant the application of a common name?

The philosophical reader may recall the discussion in Plato's *Republic* on the meaning of justice. In this discussion there appears to be an underlying assumption that there exists an abstract ideal of justice and that this ideal is recognizable as embodied in its particular manifestations. That Socrates is able to confound Thrasymachus may seem to suggest that the conception of justice does exist if not as an innate ideal at least as an ideal that can be elicited and recognized. So in the controversies on the definition of such terms as laterite and podsol there appears to be an implied assumption that there is an ideal or universal laterite and an ideal or universal podsol and that these can be elicited and defined from experience.

When the student of soils becomes first acquainted with the term podsol, he tends to assume unconsciously a realist position and suppose that all actual podsoles are particular manifestations of an ideal podsol. Hence we have the controversies centred round the definition of the podsol; for example, whether this or that character is critical in defining a podsol.

Such a belief may be untenable, because each student's conception of a podsol has been built up from his own direct or indirect experience. The podsol of Pedologist X differs from the podsol of Pedologist Y. Indeed, the same may be said of many of our conceptions, including some of the most familiar, such as table, house, plough, and motor car. We cannot, therefore, it would appear, define our ideal podsol simply from an analysis of experience or assume, with some,

that a definition is unnecessary by appealing to current usage.*

If there are certain common qualities, possession of which entitles us to speak of a class as podsol, we must consider the means by which we become aware of this. In actual experience, every student's conception of a podsol undergoes development. In the case of most British pedologists, first acquaintance is through description. In the second stage, soils are encountered in the field whose characteristics appear to agree with those learnt by description. The two most salient characteristics are, perhaps, the presence of a bleached A horizon and of a more or less ferruginous (and, by inference, sesquioxidic) B horizon. Where the student meets these characteristics he assumes that he is seeing a podsol. In the next stage, profiles possessing these characteristics are compared with a view to ascertaining what are the essential marks of a podsol. It may be found that some other characteristics are invariably present. Still other characteristics, e.g., the presence of a humic B horizon, may or may not occur. With wider experience, the student acquires a conception of a podsol that goes far beyond his original conception of a soil with a bleached A and a sesquioxidic B horizon.

If there are in a considerable group of soils a number of

*Cf. F. P. G. Guizot, *Histoire de la Civilisation en Europe* (Didier, 1859), p. 11: "... Il y a presque toujours, dans l'acception usuelle des termes les plus généraux, plus de vérité que dans les définitions en apparence plus précises et plus rigoureuses de la science. C'est le bon sens qui donne aux mots leur signification commune, et le bon sens est le génie de l'humanité. La signification commune d'un mot se forme successivement et en présence des faits; à mesure qu'un fait se présente, qui paraît rentrer dans le sens d'un terme connu, on l'y reçoit, pour ainsi dire, naturellement; le sens du terme s'étend, s'élargit, et peu à peu les divers faits, les diverses idées que, en vertu de la nature des choses mêmes, les hommes doivent rallier sous ce mot s'y rallient en effet. Lorsque le sens d'un mot, au contraire, est déterminé par la science, cette détermination, ouvrage d'un seul ou d'un petit nombre d'individus, a lieu sous l'empire de quelque fait particulier qui a frappé leur esprit. Ainsi, les définitions scientifiques sont, en général, beaucoup plus étroites, et, par cela seul, beaucoup moins vraies au fond que le sens populaire des termes." One should not conclude, however, that the popular idea of a podsol is more valid than a scientific definition.

clearly recognizable and clearly definable properties in common, then it would appear that there is a universal podsol, not in the Augustinian but in the Aristotelian sense, inherent in the group of soils and perceived and abstracted by the intellect. But here two difficulties occur: firstly there is the difficulty in the selection and perception of the critical properties, and secondly there is the difficulty of specifying these properties. In so far as the marks of a podsol do not permit of unambiguous definition the term podsol fails to represent a universal either in the Platonic-Augustinian sense or in the Aristotelian-Thomist sense, and may become no more than a mere name for a group of soils showing a general similarity. Yet the general notion of a podsol persists in the mind of the pedologist. It is framed as an abstraction from his impressions. Such an abstraction is largely arbitrary, i.e., the pedologist may select what he considers to be the most convenient criteria, subject to the limitation that these criteria are such as can be observed and defined. Precision is given by definition. This "conceptualist" standpoint is essentially practical and, if adopted, implies the drawing up of definitions for the classes of soils distinguished.

From what has been said, it would appear to be safest to regard soil classification rather as a convenient apparatus for grouping a highly complex and variable range of natural occurrences rather than as a given system of orders, genera, and species.* We should above all guard against assuming uncritically that the classes or categories such as

*We must notice a fundamental difference between the genera and species of soils and the genera and species of plants. Even if we concede individuality to a soil, in that it is composed of an ordered arrangement of horizons forming a soil profile, it is entirely the result of certain pedogenic processes acting on a certain parent material. Although a plant or an animal may be profoundly affected by its environment, on which, indeed, its very existence depends, it cannot be regarded as entirely passive. Having inherited a certain chromosome pattern, it is, within limits, an active agent, with its own reaction to its environment. When we classify soils, we are really classifying the results of the action of a variety of environmental factors, including man himself and the lapse of time, on a variety of parent materials.

podsoils, chernozems, etc., represent anything more than convenient labels for groups of soils possessing common and definable characteristics. From this, it would follow that each class should have its agreed definition, just as the terms used in an Act of Parliament are defined in the accompanying schedules. Until such definitions are generally agreed, whoever uses the term podsol without making clear the sense in which he is using the word is either falling into the error of the early medieval Realist or is using his terms loosely and without definition. Few pedologists can escape this accusation, and the present writer is no exception.

EARLIER GENETIC SYSTEMS OF CLASSIFICATION

The first real progress towards a valid system of classification was made by V. V. Dokuchaiev² in 1879. He proposed the following classification:—

A. Normal soils (unaffected by other than pedogenic processes).

Class I. Continental humus soils.

- (a) Grey northern soils (podsoils).
- (b) Chernozem (black earth) soils.
- (c) Chestnut earths.
- (d) Alkaline soils (solonetz).

Class II. Continental swamp soils.

B. Extra-normal soils.

Class III. Denuded or eroded soils.

Class IV. Alluvial and lacustrine soils.

This classification was somewhat modified later. It will be seen that, whilst Dokuchaiev's system marks an advance, in its breadth of application, on purely physical or petrographic systems, it is only devised for the classification of soils of a limited region. No place could be found in such a system for tropical soils or for the soils of Western Europe. The inclusion of extra-normal soils in a system of classification was criticized since they are not actual soils *in esse*.

F. von Richtofen,³ in 1886, proposed a system based on the mode of weathering, considered from the physical and topographical standpoint. Against this classification it may be objected that it is simply a classification of regolithic materials.

E. W. Hilgard⁴ classified soils broadly into *humid* and *arid*, and showed by numerous experimental data the important differences between the groups thus distinguished. This classification, though valuable and valid, did not, however, greatly advance the solution of the general problem.

N. M. Sibirtzev⁵ was the first to throw into clear relief the general character of the factors influencing soil formation. According to him, the variety of soils is due to variations in, (a) parent material, (b) organisms participating in the soil forming processes, and (c) physico-geographical conditions, including, above all, climate. The most important factor is the humidity and, in this connexion, Sibirtzev recognized the importance of considering rainfall in relation with temperature in assessing the humidity or aridity of a region.

Three main classes were recognized, namely, A, *zonal soils*, including the succession from laterite to tundra; B, *intra-zonal soils*, including salines, peats, and rendzinas; and C, *azonal soils*, including skeletal and alluvial soils.

The ideas of Sibirtzev, though worked out in one region, Russia, mark a distinct advance towards a world system of classification: yet, with the limited material at his disposal, and with the incomplete knowledge then available as to the constitution of the soil and the nature of the pedogenic processes, it was inevitable that Sibirtzev should lack the perspective possible to later students of the subject.

E. Ramann,⁶ in his classification of the soils of Europe, recognized with Hilgard the fundamental distinction of humid and arid soils. His first classification separates the soils in which the weathering is predominantly physical as in arctic and alpine regions from those resulting from chemical weathering. The former class include tundra and

mountain soils. The latter class is sub-divided as follows :—

A. Humid soils.

- (a) Podsoles, sub-divided into geographical groups distinguished by the degree of podsolization.
- (b) Brown earths.
- (c) Yellow and red earths.

B. Arid soils.

- (a) Chernozems.
- (b) Chestnut earths.
- (c) Grey desert, saline, and alkaline soils.

It is probably mainly to K. D. Glinka⁷ that we are indebted for our appreciation of the importance of the profile in soil studies, since his ideas have exerted the greatest influence on the present generation of students of the soil. Glinka's classification is stated in terms of maturity of profile development and the intensity of leaching by percolating waters. The following is the classification proposed :—

I. Ektodynamomorphic soils (i.e., soils in which the external factors of soil formation predominantly affect the soil character).

- (a) Laterites, red earths, and yellow earths.
- (b) Podsoles, grey forest soils, and degraded chernozems.
- (c) Chernozems.
- (d) Chestnut earths and their related types.
- (e) Peat soils and mountain soils.
- (f) Saline and alkaline soils.

II. Endodynamomorphic soils (i.e., soils in which the parent material predominantly affects the soil character).

- (a) Rendzina, or humus carbonate soils.
- (b) Skeletal soils.

The divisions of the ektodynamomorphic soils are stated in terms of the character of the leaching which has taken place (optimal moistening, excessive moistening, etc.).

CLASSIFICATION OF SOILS ACCORDING TO CLIMATE

Since the importance of climate as a factor in soil development has been realized, many attempts have been made to devise schemes for classification of climates, with special reference to their bearing on soil genesis. R. Lang⁸ proposes the *rain-factor*, i.e., the mean annual rainfall in millimetres divided by the mean annual temperature in centigrade degrees, as a basis. In its later form, Lang's rain-factor is calculated for the frost-free period of the year. By his recognition that the efficiency of a given annual rainfall as a leaching agency is modified by the temperature, Lang certainly indicates an approximate method for comparing humidities. As limits for the principal soil groups Lang gives the following figures:—

Soil group	Rain-factor
Peat soils	>160
Black earths	160-100
Brown earths	100-60
Yellow earths, red earths, and laterites	60-40
Saline soils	<40

The inadequacy of this system is evident from the assignment of the black earths to a more humid climate than the brown earths, red earths, and laterites.

A. Meyer⁹ has proposed a more accurate measure of humidity in his so-called *N-S quotient*. This is obtained by dividing mean annual rainfall by a coefficient expressing the mean deficit from saturation at the mean annual temperature.

In the following table are given the N-S quotients for the principal soil groups, calculated for the whole year, and for the frost-free period, reduced to the basis of one month.

Soil groups	N-S for year	N-S for frost-free period
Desert and desert steppe ...	0-100	0-5
Mediterranean	50-200	3-18
Chestnut earths	100-275	5-10
Black earths	125-350	8-20
Brown earths	275-400	18-30
Atlantic	375-1000	25-80
Heaths	375-700	25-50
N. German & Scandinavian	300-1200	20-85
N. Russian	400-600	20-30
Alpine	1000-4000	40-350

H. Jenny¹⁰ has shown that the principal soil types in Europe and North America are characterized by definite limits for the N-S quotient.

It is obvious, from an inspection of the figures in the above table, that the principal soil groups are not defined very closely. Indeed, some of the groups distinguished are climatic rather than soil regions. A locality with a reduced N-S factor of 25 might lie in any one of a number of groups. The classification does, however, separate the humid from the arid climates, an end which may be equally well served by Lang's rain-factor.

MODERN GENETIC SYSTEMS

During more recent years, with fuller knowledge of the soils and of the pedogenic processes occurring in different parts of the world, systems have been proposed which aim at the inclusion of all possible types. Thus, D. G. Vilensky¹¹ distinguishes four broad divisions of soils, based on the dominant factors in their formation. These are (1) *thermogenic*; (2) *phytogenic*; (3) *hydrogenic*; and (4) *halogenic*.

(1) Soils of the thermogenic divisions are developed in sub-tropical and equatorial regions, in which the dominant factor is the high temperature, which causes (a) rapid chemical decomposition of mineral silicates, and (b) rapid

mineralization of plant residues with production of carbon dioxide. Under these conditions, red and yellow loams and laterites result.

(2) Soils of the phytogenic division are mainly developed in the temperate zones under a wide range of humidity. The dominant factor is the natural vegetation. They are characterized by conditions which favour the accumulation of organic matter in the soil, and involve a less intense weathering of mineral silicates than in the thermogenic divisions. These soils include the chernozem and chestnut-earth groups, the degraded chernozems, and the podsoles.

(3) Soils of the hydrogenic division are formed chiefly in cold climates, i.e., in the tundra and the adjacent forest regions. Soil formation proceeds mainly under water-logged conditions with the development of peaty humus. Ferrous compounds such as pyrites, marcasite, and ferrous carbonate, are found in the sub-aqueous horizons. The soils include the tundra soils, the peat podsoles, and the meadow soils.

(4) The halogenic division includes soils developed in the presence of sodium salts, and includes the saline, alkaline, and soloti soils.

Intermediate divisions such as thermophytogenic and thermohydrogenic are also distinguished.

D. G. Vilensky¹², later, developed and re-arranged his system (see p. 445), which throws into clear relief the relative parts played by temperature and humidity in soil formation.

S. S. Neustreuev¹³, in an attempt to classify soils according to the processes by which they have been formed, distinguished *hydromorphous* and *automorphous* processes.

Hydromorphous processes are those which take place under the influence of ground-water, which directly, or by capillary action, moistens the soil profile. In automorphous processes, ground-water influence is absent.

D. G. VILENSKY'S SYSTEM OF CLASSIFICATION

Arid			Semi-Arid	Medium	Semi-Humid	Humid
Polar	...	Tundra	Semi-peat soils	Peat and meadow soils	—	Podsolized peat and meadow
Cold	...	Dry peat soils	—	Black meadow soils	Degraded meadow soils	Podsolized soils
Temperate		Grey earths	Chestnut earths	Chernozem	Degraded (grey forest) soils	Podsolized soils
Sub-tropical		—	Yellow soils of dry steppe	Yellow earths	Degraded yellow earths	Podsolized yellow earths
Tropical	..	Red soils of semi-desert	Red earths	Laterite	Degraded red earths	Podsolized red earths

The hydromorphous decompositions are divided into two types. In one type, capillary transport is dominant, giving rise to saline soils, and meadow soils with turf or bog iron-ore formation. In the second type, anaerobic conditions dominate profile development and give rise to meadow and peat soils.

The automorphous processes are divided into three types depending on intensity of decomposition of the mineral silicates. In the most intense type, complete decomposition into silicic acid, sesquioxides, and aluminosilicic acids takes place. Differentiation within the profile gives the sub-divisions, laterite, bauxite-laterite, and kaolinite-laterite. A less intense variety of this type is found where intermediate products of decomposition also occur. According to the type of eluviation, red, yellow, and brown earths are produced on the one hand, and podzols and solochisols on the other.

In the second type of decomposition, free sesquioxides are not formed and the principal products are acid aluminosilicic acids (clays with high $\text{SiO}_2/\text{R}_2\text{O}_3$ ratio). This type, formed under semi-humid, semi-arid and arid conditions, gives rise to chernozems, chestnut earths, and grey-brown or grey steppe soils.

In the third type of automorphous decomposition, there is only a slight chemical weathering. Products of physical

weathering predominate, whilst the fine material, if present, is mainly of external origin (wind or water transport). The soils produced by this type of decomposition include arctic and alpine soils on the one hand, and desert soils on the other.

A. Stebut¹⁴ has developed a system of classification also based on the character or tendency of the pedogenic processes. According to this author, the three principal group of processes in soil formations are :—(1) Decomposition, affecting silicate minerals (hydrolysis). (2) Synthesis of new products (formation of the weathering complex). (3) Differentiation into horizons (eluviation and illuviation).

After reviewing these processes in detail, Stebut distinguishes :—

A. UNDEVELOPED SOIL FORMATION

Class I. Lack of development due to external factors, i.e., low temperature or aridity.

Class II. Lack of development owing to nature of parent material, e.g., quartzite or quartz sand.

Class III. Development potential but unaccomplished, e.g., recent alluvia.

B. DEVELOPED SOIL FORMATION

Class I. Zeolith (Clay) formation.

Sub-class (a) In presence of alkali salts (saline and alkaline soils).

Sub-class (b) After de-alkalinization (chernozems, etc.).

Class II. Degradation.

Sub-class (a) Degradation of alkali soils (soloti).

Sub-class (b) Degradation of calcareous soils (degraded chernozems).

Class III. Destruction.

Sub-class (a) Acid humus destruction.

i. Oxidative conditions.

α. No superficial humus accumulation (brown earths).

β. Formation of peat layer (podsoles).

γ. Raw humus accumulations (peat podsoles).

- 2. Epigenetic peat formation (peat).
- ii. Reducing conditions (peats and meadow soils).
- Sub-class (b) Destruction by carbonic acid.
 - α. Without eluviation (red earths and brown earths).
 - β. With eluviation (laterites).

The above scheme gives a comprehensive view of the pedogenic processes and seems capable, by elaboration, of including all possible types and varieties of soil. In view of the importance of the character of the parent material in modifying the trend of the pedogenic processes, systems of classification such as those of Neustreuev and Stebutt mark a decided advance on systems that are stated in terms of climate alone.

The systems hitherto discussed have been based on a consideration of the pedogenic processes. An attempt to classify soils according to the character of the absorbing complex was made by K. K. Gedroiz¹⁵, who first distinguished, (1) soils saturated with bases and (2) soils unsaturated with bases. The base-saturated soils fall into (a) the chernozem group, predominantly saturated with calcium and magnesium, and (b) the alkaline group in which sodium is dominant, including the saline, alkaline, and soloti soils. The base-unsaturated soils fall into two groups, namely, (a) the podzols and (b) the laterites, including red and yellow earths, varying in the extent to which the weathering complex is decomposed.

Although Gedroiz's system is valid in itself, it seems scarcely detailed enough in its present form to serve as a world system.

The system of A. A. J. De 'Sigmond¹⁶, like that of Gedroiz, is essentially a chemical classification. The first division is into I. organic soils; II. chiefly mineral soils, with the co-operation of organic matter; and III. mineral soils. The subsequent divisions are based on the degree of "rawness" or maturity, the character of the cations associated with the exchange complex, and the degree of leach-

ing. Further subdivisions are possible according to local relief and hydrological conditions.

During the past twenty years, considerable discussion has been directed towards the institution of an agreed world system of soil classification. C. F. Marbut¹⁷, at the 1st International Congress of Soil Science, held at Washington in 1927, proposed a system of soil classification to include all soils already known or likely to be encountered.

Marbut begins by making a division of soils into *pedocals* and *pedalfers*. Pedocals, which may be regarded as synonymous with Hilgard's arid soils, are characterized by the presence in the soil profile of a zone of calcium carbonate accumulation. Pedalfers, synonymous with humid soils, show no accumulation of calcium carbonate in the soil horizons, but show a differentiation or tendency to differentiation of the clay complex in the different soil horizons, resulting in accumulation of sesquioxides.

In the next stage* of classification, the pedocals are divided into pedocals of the temperate zone and pedocals of the tropical zone, whilst the pedalfers are divided into podsollic soils and lateritic soils. The basis of classification in the second stage is, thus, temperature.

In the third stage of classification, the pedalfers are divided into the following groups: (1) tundra; (2) podsols; (3) brown forest soils; (4) red soils; (5) yellow soils; (6) prairie soils; (7) laterites; and (8) ferruginous laterites. The pedocals are similarly distinguished into, (1) north-temperate pedocals; (2) mid-latitude pedocals; (3) south-temperate pedocals; and (4) tropical pedocals. It will be seen that, in this stage of classification, the distinctions made in the second stage are included.

In the fourth stage of classification, distinctions based on rainfall are used. In the scheme, as outlined by Marbut, this is only applied to the mid-latitude pedocals, giving the succession: chernozems; chestnut earths; brown (desert) earths; and grey (desert) earths. The information at present

*The writer prefers the term *stage* to *category*, used by Marbut, and has ventured to introduce this emendation in the present account.

available does not permit a similar differentiation in the case of pedocals of warmer and colder climates. It is considered that this basis of differentiation may be applicable also to the pedalfers.

In the fifth stage of classification, soils are differentiated on the basis of the degree of maturity of the soil profile.

In the sixth stage of classification, distinctions based on the parent material are used, giving the soil series (p. 505), whilst in the seventh stage, the texture is used, giving the type.

TABLE XLV.—SCHEME OF SOIL CLASSIFICATION BY C. F. MARBUT

Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7
PEDOCALS	Pedocals of Temperate Climates	North- Temperate		Subdivision of categories of Stage 4 according to maturity of profile	Subdivision of categories of Stage 5 according to parent material	Subdivision of categories of Stage 6 according to surface texture
		Mid-Latitude	Che:nozems Chestnut- Earths Brown Soils Grey Soils			
		South- Temperate				
	Pedocals of Tropical Climates					
PEDALFERS	Podsolie Soils	Tundras		Subdivision of categories of Stage 4 according to maturity of profile	Subdivision of categories of Stage 5 according to parent material	Subdivision of categories of Stage 6 according to surface texture
		Podsols				
		Brown Forest Soils				
		Prairie Soils				
	Lateritic Soils	Yellow Earths				
		Red Earths				
		Laterites				
		Ferruginous Laterites				

Marbut's classification is shown schematically in Table XLV. It will be seen that spaces are left for the insertion of groups still to be identified and described, so that, with some necessary modifications, the scheme does give a basis for a world-wide system of classification. It will be noticed, however, that no place is found for soils developed under conditions of impeded drainage, such as meadow and vlei soils. Such soils being intra-zonal or azonal, may not be considered as demanding a place in the world-system, on

TABLE XLVI.—AMERICAN CLASSIFICATION OF ZONAL AND AZONAL SOILS

Zonal soils	Fedocals	Soils of the cold zone		1 Tundra soils
		Light coloured soils of arid regions	2. Desert soils	
			3. Red desert soils	
			4. Sierozem	
		Dark coloured soils of arid, sub-humid, and humid grass-lands	5. Brown soils	
			6 Reddish-brown soils	
	7 Chestnut soils			
	Pedalfers	Soils of the forest-grassland transition	8 Reddish-chestnut soils	
			9. Chernozem soils	
			10 Prairie soils	
		Light coloured podsolized soils of the timbered regions	11 Reddish prairie soils	
			12 Degraded chernozem soils	
			13 Non-calcic brown soils	
		Late-ritic soils of forested warm temperate and tropical regions	14. Podsol soils	
			15 Brown podsolc soils	
16 Grey-brown podsolc soils				
17. Yellow podsolc soils				
18. Red podsolc soils				
19 Yellowish-brown lateritic soils				
Intrazonal soils	(Halomorphic saline and alkaline) soils of imperfectly drained arid regions and littoral deposits	20 Reddish-brown lateritic soils		
		21. Laterite soils		
	Hydromorphic soils of marshes, swamps, seep areas, and flats	(Halomorphic saline and alkaline) soils of imperfectly drained arid regions and littoral deposits	1 Solonchak or saline soils	
			2. Solonetz soils	
			3 Soloth (soliti) soils	
			4 Wiesenböden (meadow) soils	
			5 Alpine meadow soils	
			6 Bog soils	
		Calomorphic soils	7 Half-bog soils	
			8 Planosols	
			9 Ground-water podsol soils	
	Ground water laterite soils	10. Ground water laterite soils		
		11. Brown forest soils (Braunerde)		
		12 Rendzina soils		

account of their dependence on special local conditions of topography and drainage. They are, nevertheless, of widespread occurrence and, in the writer's opinion, should form a major group. Neustreuev, indeed, thus recognizes them in his class of hydromorphous soils.

Marbut's system has been further developed by the United States Soil Survey¹⁵ workers and the system at present (1948) in use is shown in Table XLVI, which gives the classification of zonal and intrazonal soils. Azonal soils are classified simply with lithosols, alluvial soils, and dry sands.

E. H. Del Villar¹⁶ in his memoir on the soils of Spain and Portugal has proposed a system of classification that is strictly based on the characters of the soil profile and is set out in the form of a "Key," as follows:—

1	{	Soils developed with free aerobic metabolism	2
		Soils developed under conditions of permanent or intermittent waterlogging (hydropedic) ..	7
2	{	Soils with a high proportion of soluble salts.	
		<i>Saline series.</i>	
3	{	Soils with mineral proportions of or no soluble salts	3
		Soils with a high proportion of the sodium ion in the absorbing complex	
		<i>Alkaline series.</i>	
4	{	Soils without this high proportion of the sodium ion	4
		Soils with calcium carbonate in the edaphic horizons.	
		<i>Calcureous series.</i>	
5	{	Soils without calcium carbonate in the pedological horizons	5
		Soils with humus as a fugitive constituent, in which leaching of silicic acid leaves a high proportion of sesquioxides in the profile.	
		<i>Allitic series.</i>	
6	{	Soils with humus accumulation in which leaching leaves a high proportion of silicic acid in the profile	6
		Soils with soluble acid humus and marked leaching of sesquioxides from the upper horizons.	
		<i>Acid-humic series.</i>	
7	{	Soils with mild humus and less intense leaching.	
		<i>Siallitic series.</i>	
		Soils with disturbance of aerobic metabolism by intermittent flooding.	
		<i>Alluvial series.</i>	
		Soils with waterlogging, permanent or intermittent, through the presence of ground-water.	
		<i>Gley series.</i>	

This classification can be still further simplified by grouping the eight series into four great cycles:—

- I. Saline-alkaline cycle.
- II. Calcareous cycle (approximately Marbut's pedocals, but with difference of definition).
- III. Sesquioxidic cycle: allitic series, siallitic series and acid-humic series (approximately Marbut's pedalfers, but with difference of definition).
- IV. Hydropedic cycle: alluvial and gley series.

Del Villar divides his series in *stages* and *phases*, the former term denoting a point in the evolution of a series, and the latter term a variant due to causes apart from the characteristic pedogenesis of the profile. Typical stages are *immature*, *mature*, and *post-mature*. A soil with its natural characters is considered to be in its *primary phase*: the succeeding phases are termed *secondary*, the most important secondary phase being the *agropedic* phase, i.e., the phase resulting from cultivation.

Our knowledge of the soils of the world is probably not yet sufficiently complete for the formulation of a system to include all possible kinds of soil. The following system is put forward tentatively by the writer, as including most of the known soils of the world. It is based on the type of leaching to which the profile has been subjected.

Soils with free drainage	Completely leached (pedalfers)	Presence of raw humus	{	1 Humus podsols
			{	2 Iron podsols
		Absence of raw humus	{	3. Brown earths
			{	4. Degraded chernozems
			{	5 Prairie soils
			{	6. Yellow podsolic soils
	Incompletely leached (pedocals)	—————	{	7. Red podsolic soils
			{	8 Tropical red loams
			{	9 Ferrallites
			{	10 Chernozems
			{	11. Chestnut soils
			{	12. Brown desert soils
			{	13 Grey desert soils
Soils with impeded drainage	Absence of soluble salts	Sub-arctic	—	14. Tundra
		Temperate	{	15. Gley soils
			{	16 Gley podsols
			{	17. Peat podsols
	Presence of soluble salts	Sub-tropical and tropical	{	18 Peat soils
			{	19. Vlei soils
		—————	{	20. Saline soils
			{	21. Alkaline soils
			{	22. Soloti soils
			{	

SIGNIFICANCE OF CLIMATE, GEOLOGY, AND
TOPOGRAPHY

Mature soil profiles are the result of the pedogenic processes acting on different materials, which may be either consolidated rock, or unconsolidated *débris*, such as alluvium or loess. In arriving at a classification of profiles, it is of importance to obtain a clear view of the relative weight to be assigned to the pedogenic processes on the one hand and to the parent material on the other as factors in soil development.

In the earlier systems of soil classification, the dominant factor was considered to be geology, as affecting the parent material. The studies of the Russian school of pedologists, with their emphasis on climatic factors, have led to greater weight being assigned to the pedogenic processes, which were considered to be capable of obliterating the differences due to parent material. It was found, for example, that chernozem profiles could be developed from parent materials which differed considerably in lithological character. On the other hand, instances were brought forward in which the same parent material gave rise to totally different soils under the action of different pedogenic processes. A classical example is that given by G. Wiegner²⁰ of two dolerites of approximately the same composition, one of which yielded under English conditions a grey clay, whilst the other, in Southern India, gave rise to a laterite (*ferrallite*), consisting almost entirely of hydrated sesquioxides.

Since the pedogenic processes are mainly governed by temperature and by the balance of rainfall and evaporation, it is natural that systems of classification should be elaborated that are essentially climatic. Indeed, the criticism might be made that such systems are classifications of climate rather than of soil. Even in classifications, such as that of Marbut, which meet this objection and purport to be based on the actual soil characters, it is impossible to avoid defining the classes in terms of climate.

Now, whilst it is certain that the major differences

between soils are due to the effect of climate operating through the pedogenic processes, the geological factor cannot be eliminated even in the definition of the great soil groups. Many instances may be given in which, under a similar set of pedogenic processes, different parent materials have given rise to soils which must be assigned to different world groups.

B. Polynov²¹, in a discussion of the rôle of geology in soil formation and its significance in classification, directs attention to the effect of parent material in modifying the occurrence and distribution of the great soil groups. Quartzose sand enlarges the area of podsoles both at the northern and southern limits. Sandy parent materials also increase the desert area. For example, in the Caspian region, whilst loam soils belong to the chestnut earths, sandy soils have a desert character.

In South-Eastern England, typical podsoles are developed on the light sands and gravels of the Bagshot Beds. Under the same climate, other parent materials yield brown earths and even soils which may have affinities with terra rossa. It may be said of Britain as a whole that the lightest sands form podsoles, whilst parent materials of heavier texture and higher base-status yield brown earths.

In the Transvaal, the weathering of diabase yields red loams which are probably related genetically with the tropical red loams, whilst norite gives rise to black soils, the so-called black turf soils, which resemble, in some respects, vlei soils and must certainly be assigned to a major group distinct from the red loams.

W. H. Bryan and H. J. G. Hines²² have reported even more striking instances of variety of soil type under the same climate in Queensland. There, within a comparatively small area of approximately uniform climate, soils comparable with the chernozems, podsoles, red earths, yellow earths, and laterites of other countries are to be found. This diversity can be satisfactorily explained by considerations of parent material and topographical relief.

The effect of topography was recognized by the late G. Milne²⁴, who found in tropical Africa a regular pattern of soils determined by surface relief, with red loams in the higher situations and vlei or mbuga soils in the depressions. He proposed the recognition of a complex of this type under the name of "catena." The catena concept has been further developed by T. M. Bushnell³⁴ in the light of N. American experience.

Soils derived from calcareous parent materials exhibit certain distinctive features. On the one hand are the red soils of the terra rossa group, whilst on the other hand are the grey or black soils of the rendzina group. It appears that, so long as the calcium carbonate of the parent material can maintain a state of base-saturation, the soil is of a greyish colour with a weathering complex relatively rich in silica and a dark-coloured type of humus. But when desaturation occurs through leaching—a state which may be reached before the complete disappearance of coarsely fragmental limestone—desilicification ensues and reddish or reddish-brown soils are formed, containing free sesquioxides in the weathering complex. This stage is reached most readily in soils derived from hard limestones, which thus tend to be associated with reddish soils, whilst soft limestones generally give rise to greyish or dark-coloured soils of the rendzina group. The ease with which leaching occurs in hard limestone soils, the rapid mineralization of plant residues consequent on their warmth and aeration, all contribute to confer on such soils the characters of soils of warmer climates. Mature leached limestone soils of sub-tropical and even of temperate regions show considerable resemblance to tropical red loams.

It is obvious, therefore, that a classification of climates without reference to geology can give only a partial classification, even of the major soil groups. A map showing the major soil groups must in many cases show different groups occurring under the same climatic conditions.

In the more detailed classification of the soils of a

limited region, geology is frequently the main guide. After all due weight has been given to climatic factors, the most fruitful principle of classification of British soils is the geology, if consideration be given to lithological variations.

Even in a region of uniform climate, geology does not always provide a sufficient basis for differentiation, for important modifications are introduced by topography. Some of these modifications are in a sense geological. The difference between the thin soils of the uplands and the deep colluvial soils of valleys may be expressed in terms of superficial geology. In a detailed soil survey, such distinctions as *shallow phase* and *deep phase* are of great importance.

Topography exerts its principal effect on soil development by its bearing on water movements. The same parent material gives rise to markedly different soil profiles according to whether the drainage is free or impeded. With free drainage under humid conditions, the soil is more strongly leached of bases than where the drainage is impeded. This leads to degradation of the clay complex with liberation of silicic acid and sesquioxides. In cool climates, an acid type of organic matter is formed from the residues of vegetation, and a podsol profile results. The brown earths represent an intermediate stage, but seem to be essentially similar to the tropical red loams.

In low-lying situations with a high water-table and impeded drainage, the profile development will depend upon the extent to which the accumulation of acid organic matter occurs. In regions of high rainfall and moderate temperature, a peaty layer is formed and a bleaching of the mineral soil through removal of sesquioxides occurs, resulting in a peat podsol. This process may, indeed, occur in water-logged situations in the tropics.

Where peat is not formed, gley soils occur in cool and temperate climates. These are characterized by grey horizons with rusty mottling in the vicinity of the fluctuating water-table. In similar situations in the tropics, black and

grey soils are found, also with rusty mottling, and even concretionary deposits, in the vicinity of the water-table.

The mineral colour of soils with impeded drainage is generally grey owing to the presence of ferrous compounds consequent on deficient aeration. Further, the low degree of leaching and, in many cases, the relatively high base-status result in the development of a siliceous type of clay complex.

The occurrence of saline and alkaline soils can generally be attributed to the effect of topography operating through drainage conditions.

We have referred repeatedly to climate, geology, and topography as bases of classification. It is necessary to emphasize again that the object to be attained is a classification of soils. The logical order of procedure is first to classify soils and then to attempt correlations with climate, geology and topography. Thus if a study of the soils of a given area of uniform climate shows that they fall into three broad categories, one consisting of soils derived from non-calcareous shales, another of soils from granite, and the third of soils from limestone, it is permissible in describing and defining these categories to allude to the geological parent material, by naming the categories shale, granite, and limestone soils, respectively. Similarly with climate in a region of uniform geology. Climate, geology, and topography, are valuable in arranging the soils of countries, regions, or districts into categories. In an universal system, however, they cannot be so used. The category podsols must cut across geological and even climatic divisions and podsols can be defined only in terms of actual soil profile characters.

The relative weight to be assigned to the factors geology, climate, and topography, will depend on the circumstances of a particular region or country. In Russia, for example, climate has proved the most fruitful principle of classification. In Great Britain, geology gives the clearest clue to soil differences. In every region, however, topo-

graphy, as affecting the drainage and as modifying the depth of accumulation of the products of weathering, enters as an important factor in classification. The principle to be observed in every case is to classify on the basis of the soil itself, using the profile as the unit of study.

GENETIC INTER-RELATIONSHIPS AMONG SOILS

We have already referred (p. 433) to H. Jenny's attempt to express the dependence between soil properties and pedogenic factors by mathematical functions. In a later paper²⁵ he postulates "five canonical functions of pedology." Denoting the sum of the properties of a soil by $E(s)$,

$$E(s) = f(c, o, r, p, t, \dots).$$

Where c =climate, o =organisms, including vegetation, r =topographical factors, including hydrology, p =parent material, and t =time. The various sequences are defined as:—

Climosequences	$E(s) = f(c)o, r, p, t$
Biosequences	$E(s) = f(o)c, r, p, t$
Toposequences	$E(s) = f(r)c, o, p, t$
Lithosequences	$E(s) = f(p)c, o, r, t$
Chromosequences	$E(s) = f(t)c, o, r, p$

Expressed in non-mathematical terms this means that an assemblage of soils can be arranged in sequences to show the effect of each individual factor, when all the others are assumed constant. Thus by climosequence he means a range of soils in which the only variable is the climate, and so on. He gives examples from California of a number of sequences, the toposequence being split further into a climosequence (depending on slope) and a hydrosequence, depending on hydrological conditions.

S. A. Wilde (*Forest Soils*, p. 13), developing an idea of Dokuchaiev, expresses the relationship between soil and pedogenic factors as an integral:

$$S = \int (g, e, b) dt$$

where g=geological substratum, e=environmental influences, b=biological activity, and t=time.

C. G. Stephens²⁶ has further examined and developed this line of approach to soil relationships. He points out that in nature the variables in Jenny's equations are not completely independent. Thus—

c	may affect	o, r, w, p, s,	but not t
o	„ „	c, w, p, s,	„ „ t, r
r	„ „	c, o, w, p, s,	„ „ t,
w (hydrology)	„ „	o, p, s,	„ „ t, c, r
p	„ „	o, r, w, s,	„ „ t, c
t	„ „	c, o, r, w, p, s	
s	„ „	o, r, w, p,	„ „ t, c

He gives a complete list of all possible relationships in the form of partial differentials, e.g., $\frac{\partial s}{\partial c}$, $\frac{\partial s}{\partial o}$ etc. He considers that the relationship between a soil and its factors is best expressed as

$$s=f(c, o, r, w, p, t)dt$$

in which t is independent and c, o, r, w, p can have both dependent and independent status.

From a study of published descriptions of certain groups of Australian soils he constructs a number of diagrams showing their genetic relationships and the interaction of the variables.

The relationships between soils of a region are sufficiently involved, and even greater complications and cross relationships may be expected when a larger assemblage of soils is handled. Stephens remarks that if a genetic classification of soils is to be correlated with a morphological classification, the arrangement will need to be on a multidimensional basis. It is therefore hopeless to expect perfect correlation between large scale climatic maps and soil maps, and the same may be said of the other correlations. For the present, soils can be mapped only on their observable morphology and the pedologist must be prepared

to find that the same, or apparently the same, soil profile may be produced by different combinations of pedogenic factors.

PROVISIONAL CHARACTER OF EXISTING SYSTEMS OF CLASSIFICATION

The attempts which have been made to devise a world classification of soils have been encouraged by the impression that identical, or nearly identical, soils can occur in different parts of the earth. Thus, it was generally considered that, in the high plains of the United States, there are soils that can be classed with the chernozem and related groups of Russia. In view of the qualitative character of much of the information relating even to such an important group as the chernozems, it would be safer to regard such correlations as provisional, and to await the accumulation of such a body of quantitative data as shall place their identity or dissimilarity beyond doubt.

This view does not imply that the proposed systems of classification are not worthy of serious consideration. On the contrary, so far as they are based on a considered review of intensely studied soil types, they are of the highest philosophical value. Their provisional character consists in the uncertainty of their application to soils that have not yet been subjected to intensive study, or which have been described only in qualitative and, therefore, subjective terms.

And thus, whilst the various systems proposed may be trustworthy for the soils on which they are based, and suggestive for soils yet to be studied, the immediate task is to enlarge and intensify our information as to the constitution and genesis of the soils of different parts of the world. And if, as is possible though not proven, the soils of the world can be grouped into a finite number of classes, then the modification of existing systems and the synthesis of local classifications will ultimately lead to a world system.

For these reasons, the provisional character of all methods of soil classification hitherto proposed cannot be too strongly emphasized. There are large tracts of the earth's surface where soils have been so imperfectly investigated that no trustworthy conclusions can be drawn as to their relationships. Even for the better known regions, the data are frequently of a qualitative character, and the deductions therefrom may be fraught with serious errors.

Whilst the pedologist should always strive to relate his soils to those already described in other countries or regions, he should not adopt uncritically types recognized under different conditions of topography, geology, and climate. He should, in the first place, distinguish the different profiles in the region for which he is responsible. Each profile should be described with the fullest qualitative and quantitative data, including information as to mechanical composition, structure, base-status, salt content, and the composition of the clay fraction in each distinguishable horizon. In addition, data should also be obtained for the organic matter profile, making use of any methods of fractionation which may become available. With the aid of such data, the profile types should be arranged into a system, which can then be related to systems recognized in other countries.

It is along these lines, in the writer's opinion, that a satisfactory world system of classification will eventually be reached. In some cases it will be at once possible to identify a soil type in one country with a well known soil type already recognized in another country, but the factors of soil formation and the parent materials on which they operate are so diverse that it must be an exceptional case for a soil type isolated, say, in Europe, to be completely identifiable with a type in North America or Australia. Premature identification may be a source of ever-widening error.

There are, therefore, two groups of problems. The one is the philosophical problem of devising a world classification of soils and the other is the practical problem of arranging the soils of a limited area, it may be a parish, a

county, a province, or a country, into a logical system among themselves. We shall discuss this second problem, the problem of the soil surveyor, in Chapter XVIII.

The extension of the broad world classification to include the agriculturally important but philosophically subsidiary distinctions recognized in soil surveys is a task that may well be postponed until more information is available. It may be doubted whether the classification of soils can ever be stated in terms of families, orders, genera, and species, as is possible in the case of animals and plants. Even if it were possible, the distinction between one soil species and another would be far more blurred than in the case of animal and vegetable species.

Finally, one defect of existing schemes may be noticed. In nearly all cases, the ultimate soil-classes are named in terms of colour. Thus, we have red earths, yellow earths, brown earths, and black earths, as well as Russian terms such as podsol, chernozem, and sierozem, which are also colour names. It is obvious that the description "black earth," whether in English or Russian, can apply to soils other than the chernozem *sensu stricto*. Similarly, red earth, merely as a description, can apply to a wide range of genetically distinct soils. If a descriptive nomenclature is to be used, and this seems inevitable in a major classification, it might be better to sacrifice brevity for precision, and to abandon podsol, chernozem, and similar terms as scientific names.

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CHAPTER XVII

THE GEOGRAPHY OF SOILS

IN the present state of our knowledge, it is, perhaps, hazardous to attempt to give any general view of the soils of the world, for large areas remain pedologically unexplored. Such information as can be given about the soils of these regions is, to a large extent, conjectural, and based on the collateral evidence of climate, topography, and vegetation. Nevertheless, a review of the soils of the world, in the light of such knowledge as we possess, is desirable, and will be attempted, with all reserve, in the present chapter.*

It is only to be expected that fuller information is available in some countries than in others. The lack of accurate data is most marked in tropical regions, where the material hitherto available has consisted mainly of analyses of soil samples made for practical requirements. Only during recent years have descriptions of actual tropical soil profiles appeared in the literature of the subject.

EUROPE.

As may be expected, the information concerning soil is more abundant in Europe than in any other portion of the earth, with the possible exception of the United States; but there are still considerable gaps in our knowledge. A large amount of material is available relating to the soils of Russia, Poland, Scandinavia, Holland, Germany, the former Austro-Hungarian Empire, and Great Britain. Considerably less material exists for judging the soils of Southern Europe.

At the instance of Commission V of the International Society of Soil Science, a soil map of Europe was pre-

*For the sake of convenience in the narrative, the sources are not given in the text, but are set out at the end of the chapter.

pared under the direction of Professor H. Stremme, of Danzig. A provisional map on the scale of 1:10,000,000, with an accompanying memoir, was published in 1927, and a revised map on the scale of 1:2,500,000 in 1935. Making allowance for the somewhat Procrustean system of classification and for the uncertainty as to the position of the soils of certain regions in this system, it is yet possible to make certain generalizations as to the distribution of soils in the different countries.

Great Britain. The soils of Great Britain belong mainly to the podsollic group, if in this group we may include the brown earths.* In the provisional soil map of Europe, most of the eastern and southern part of Britain is shown as brown earths, with podsoles lying to the north and west. Recent experience has shown the important part played by topography and, above all, by the parent material in determining the character of British soils. The tendency to podsolization becomes more pronounced in moving from south-east to north-west, but quartzose sands in S.E. England carry well developed podsoles, whilst, even in the most humid regions of the west, brown earths occur where the parent materials are such as to yield soils of intermediate or heavy texture. Further, the relative immaturity of much of our British soil results in the parent material playing a great part in determining actual soil characters. Age-long cultivation has probably produced considerable modifications, so that soils which were originally podsoles or meadow soils have now become brown earths.

Given the importance of geology, there appears to be ample justification for reviewing the soils of Britain in terms of the parent materials which have produced them.

Pre-Cambrian rocks attain their greatest extent in the Scottish Highlands, where they are represented by schists

*It should be noted that whilst the majority of the well-drained soils of Britain may be described conveniently as brown earths, there is often, particularly in the west, a slight greyness in the surface soil and a development of brownish colour in the sub-soil that betokens a certain degree of podsolization. Perhaps the American term "grey-brown podsollic soils" would be more apt.

and sandstones. In the cultivated valleys and foothills, the soils, though generally immature, appear to be usually of a brown earth type where well drained, whilst, in upland areas, podsoles are more prevalent. With them are associated gley soils, peat podsoles, and peats. The most considerable area of Pre-Cambrian rocks in Southern Britain is in Anglesey, where brown earths are found derived from schists and schistose drifts, with occasional patches of iron podsoles in uplands, particularly in association with quartzites.

There is a general similarity between soils derived from igneous and pyroclastic rocks of all periods. Further, with the relative immaturity of British soils, the differences between the weathering of basic and acid rocks are not so marked as in warmer climates. Generally speaking, igneous rocks give rise to brown earths in lowland areas and podsollic soils, sometimes truncated by erosion, in uplands. The soils of the more acid rocks, such as granite and rhyolite, more readily undergo podsolization than those derived from intermediate and basic rocks.

The soils derived from igneous rocks of all periods are generally similar to those derived from crystalline metamorphic rocks. Although, on account of the relative immaturity of British soils, the distinction between the weathering of acid and of basic rocks is not so marked as in warmer climates, differences are observable. Whilst soils derived from acid and intermediate rocks may show varying degrees of podsolization, basic rocks, such as dolerite and norite, yield brown soils of neutral or sub-neutral reaction, showing no evidences of podsolization. We have, thus, from acid and intermediate rocks, a range from brown earths to podsoles, the latter predominating in wetter districts and on the more acid rocks such as granite and rhyolite. In upland regions, these podsoles may be truncated by erosion. Over basic igneous rocks, we have brown earths only, in varying stages of development.

The sedimentary rocks of Cambrian, Ordovician,

and Silurian age (excepting hard grits, which appear to behave pedogenically as igneous rocks) give rise, in lowland areas, to soils which are generally similar in character and may be classed together as brown earths. But, since they occur mainly in the west under high rainfalls, drainage impedance is frequent and considerable areas of wet soil result. The uplands are occupied by shallow podsoles, often truncated by removal of the A horizon so that the surface soil is of a markedly sesquioxidic character. Gley soils, peat podsoles, and mountain peats are of frequent occurrence. The soils of the Devonian shales in Devon also may be grouped with those of the older Palæozoic sediments.

The Old Red Sandstone gives rise mainly to brown earths, but some of the quartzose conglomerates carry podsoles, as in W. Glamorganshire. The soils of the uplands exhibit various stages of podsolization, modified by erosion. The bright red colours of certain soils of this formation are to be attributed to the effect of the parent material.

The character of the soils of the Carboniferous Limestone is greatly influenced by topography. The calcareous colluvial and glacial drift soils may have affinities with the rendzinas. On the other hand, there are thin leached upland soils which may be assigned to the group of red and brown limestone soils. (See Chapter XV.) In some cases, soil formation is almost entirely absent, and limestone pavements result.

The non-calcareous sedimentary rocks of the Carboniferous system give rise mainly to brown earths, but heavy texture sometimes results in drainage impedance and the development of gley soils.

The Permian formation in England is represented by the Magnesian Limestone, whose associated soils resemble, in many respects, those of the Carboniferous Limestone, and by breccias, marls, and sandstones, whose soils may be grouped with those of the Trias.

The Trias may be considered briefly under the headings, sandstones and marls. The sandstones, which are generally

red in the Bunter, but sometimes brown or grey in the Keuper, give rise to a succession varying from brown earths to podsols. The distinction appears to depend on the actual character of the material, the more quartzose sandstones and the pebbly conglomerates, with their associated drifts, being most apt to become podsolized. Drainage conditions, by their effect on leaching, also play a part. Podsollic characters would, doubtless, be more marked but for the conservative effect of cultivation and manuring on agricultural soils. Gley and peat soils are of frequent occurrence in certain drift areas of Cheshire and Shropshire.

The Triassic (Keuper) marls are mainly reddish clays, sometimes containing calcium carbonate, which, however, is generally leached from the surface horizons. The derived soils are brown earths and gley soils.

Bright red soils occur frequently in association with certain upper horizons of the Carboniferous system, the Permian sandstones, and the Triassic sandstones; but it should be clearly understood that the colour is due to the character of the parent material and is not attributable to contemporary pedogenic processes.

In considering the Jurassic and later systems, with their rapidly alternating succession of sediments, we shall find it convenient to consider them from the point of view of lithology, which, subject to topographical factors, appears to supply an adequate classification.

Soft limestones, such as the Lower Lias and parts of the Chalk, give rise to greyish-brown, greyish, and in some cases, white soils, which may be grouped with the rendzinas. In situations where calcium carbonate is leached away, they may give brown or reddish-brown soils that are essentially brown earths.

Hard limestones, such as the Forest Marble and the Kentish Rag, may give reddish-brown soils akin to the brown earths and, possibly, to terra rossa. Where base-saturation is maintained, the grey or grey-brown rendzina type persists.

Clays, such as the Oxford, Kimmeridge, and Gault clays, generally suffer drainage impedance, and their associated soils may be grouped with gley soils. Horizons of calcium carbonate or gypsum accumulation sometimes occur in the zone of drainage impedance. With free drainage, brown earths are formed.

The sandstones of the Jurassic and later formations are, for the most part, soft or unconsolidated. The derived soils form a range varying from brown earths to podsoles according to the lithological character of the parent material. Quartzose sands and gravels, such as the Bagshot Beds, form well-developed podsoles with massive humus and iron pans.

The nature of the soils derived from glacial drifts is generally governed by the character of the contributing materials and by the topography and drainage.

Alluvial soils occur in all parts of Britain. They are generally immature, except in the case of old river terraces, where in some cases a certain amount of profile development may have occurred. Dune soils in varying stages of fixation occur in coastal districts.

The most notable development of lowland peat is in the Fen district. Upland and mountain peats occur commonly in elevated areas, particularly in the west.

Much of the soil of upland areas in Britain is very immature and may be described as skeletal. It is probable that erosion has produced considerable modification, so that the shallow profiles encountered are considerably truncated, and represent only the lower horizons of the original profiles existing under the primitive forest cover, which extended up to about 1,500-1,700 feet above the sea level.

Scandinavia and Finland. A considerable proportion of Scandinavia is occupied by immature mountain soils with podsollic tendencies. The lowlands of Scandinavia and Finland are occupied by glacial deposits, including boulder clays, lacustrine clays, and fluvioglacial sands and gravels. Podsoles, in varying stages of development, form

the typical soil group of these regions and are developed naturally under birch forest, coniferous forest, or in Denmark, heath. Brown earths occur in parts of Southern Scandinavia under deciduous forest. The topography and hydrological conditions associated with a region of glacial drifts result in the widespread occurrence of peats and meadow soils in low-lying situations. In an area of low rainfall in Central Norway, saline soils are encountered.

Iceland. The prevalence of basic parent materials (basalt, liparite, etc.) strongly affects the pedogenic processes. Although as might be expected, Icelandic soils are rich in humus, podsollic soils are not usual. The high base reserves of the parent materials maintain reactions not far below neutrality. From the little that is known of the soils of this island, it would appear that they present a striking instance of the effect of geology in modifying pedogenic processes.

Poland. The soils of Poland show a complicated distribution depending on variations in parent material and in surface relief. Over a large part of the country, chalk occurs covered by loess, which has been partially removed by erosion. Rendzinas occur on predominately calcareous parent materials, chernozems and degraded chernozems on loess, whilst soils varying from brown earths to podsols are developed from loessial debris and from glacial deposits. A considerable area of meadow soils with associated peats occurs in the Pripet marsh region of Central Poland.

Switzerland. The soils of Switzerland are dominated by the mountainous character of the country and are mainly skeletal and undeveloped. This applies both to the mountain soils and to the younger alluvia of the valleys. Rendzinas are developed on calcareous rocks in north and central Switzerland, whilst podsols and podsollic soils occur in the southern part of the country, where development is possible.

Germany. Stremme divides the soils of Germany into three zones, namely, the northern coastal zone, the middle loess zone, and the south and south-east mountain zone.

Along the northern coasts, sands and loams are developed from glacial sands and boulder-clays. Forest soil types are also represented. There is a fringe of marshes along the coast and in the west are heath and moorland soils.

In the north-east German plain with a recent glacial landscape, podsollic soils and podsolized forest soils occur principally on the glacial drifts; brown forest soils (brown earths), characterized by a brown B horizon, are also present. The textural types are principally sands and loams, less frequently clays. To the west and south, soils belong principally to the drifts of the older glaciations. The principal soil is the strongly podsolized forest and heath soil, often with ortstein and raw humus. There are also mineral and humous soils of impeded drainage. Among the latter there are numerous areas of high moor peat. Brown podsolized forest soils are not so common. The dominant textural type is sand. It is probable that the soils of this region were originally rich in lime but have now become decalcified. The older drifts are often covered by younger deposits of glacial sands, which are particularly poor as soil formers.

Through Middle Germany there stretches a loess zone with different kinds of soil. In some places chernozem is developed and elsewhere, as in the south-west, degraded chernozems. Where the loess occurs in strong relief, erosion has taken place and undeveloped soils occur. The mountain region in mid-Germany shows a strong influence of topography on soil formation. In the Bunter sandstone region of mid and west Germany undeveloped soils occur on the slopes. Immature podsollic soils occur on acid parent rocks such as granite, sandstone, etc. Even the more basic rocks in this region may give immature podsollic soils. Rendzinas are infrequent because of erosion on the hillsides, whilst in the bottom lands brown forest soils are developed.

In the Upper Rhine Valley are brown forest soils, together with steppe soils. The Upper Rhine plain is mainly sand and loam covered with loess. The celebrated

wine soils of the Rhine Valley are developed from schistose rocks. In the mountains around the Rhine Valley are partly podsolized brown forest soils.

Czechoslovakia, Austria, and Hungary. A wide range of soils is shown in these countries. In the mountainous regions, there are immature skeletal soils generally of a podsollic type, but including some rendzinas. Among mature soils of the lowlands the brown earths predominate, but the Central Hungarian plain carries dry steppe soils with associated saline and alkaline (szik) soils. Red soils occur in Moravia and Hungary (nyirok soils) which appear to have affinities with terra rossa but may have resulted from Tertiary weathering.

Italy and the Adriatic coastal lands. The soils of northern Italy and the western coastlands of the Adriatic are mainly brown earths. Alluvial soils occur in the Lombard plain. Elsewhere in Italy, including Sicily, skeletal soils, markedly affected by erosion, prevail. The tendency, however, is towards the development of red soils, which may probably form a transition between the brown earths and the tropical red loams and red earths. Terra rossa and "karst" soils (eroded terra rossa) occur on limestone in the N.E. coastal regions of the Adriatic. In this region salt-bearing soils also occur.

France. Podsollic soils are well developed in western, central and south-western France, e.g., in Brittany, the Paris region, and the Vosges, on sands, sandy or gravelly clays, quartz schists, and certain acid igneous rocks. Typical podsoles are comparatively rare. They occur under forest (conifers, oak, beech) or heath. Leached soils are widespread. They are often the best agricultural soils. Developed on loess, they form the soil of the great intensively cultivated plateaux of the north-west (Brie, Beauce, Vexin, Santerre). Brown soils are not so common, yet they occupy considerable areas in certain of the regions mentioned (Beauce), also in Alsace, Lorraine, Jura, and in the Midi region. On plateaux, they are generally developed on loess

loams, light or sandy calcareous materials, marls, and sometimes on clays, clay shales, and occasionally on fine sands. They may be very fertile, e.g., the black marl soils of Limagne. The "bocages," grass fields surrounded by woody hedges, so common in the west, correspond with soils of this type developed on rather impermeable parent materials. Elsewhere they are found on slopes. Their agricultural value depends to a large extent on their depth.

On calcareous parent materials, particularly on the sides of valleys, are found rendzinas, generally rather shallow and gravelly. They occupy considerable areas on certain dissected plateaux (Champagne, Poitou, Berry, Bourgogne). They also occur in the warmer regions of the south and south-west.

The red Mediterranean soils, often eroded, occupy parts of the south-east (lower valley of the Rhône).

Recent alluvia are comparatively little developed. The coarser types are poor, but the finer textural types carry rich pasture and may be intensively cultivated. In the coastal regions certain alluvial soils are of high agricultural value, e.g., in Flanders, Brittany, Vendée, and Poitevin.

Skeletal soils and alluvial soils, often of very poor texture, occur in the mountain region of the Alps, Pyrenees and Vosges.

Holland. A large proportion of this country is occupied by estuarine alluvium reclaimed from the sea. The soils of the older reclamations may possibly be assigned to the meadow soils and brown earths. Podsoils and upland peats occur in northern Holland.

Spain and Portugal. In the north and west of the Peninsula the soils are generally of the brown earth or podsollic type. The west central part, for example, much of Algarve (Portugal), Extremadura (Spain), and the foothills of the Sierra Guadarrama is occupied by soils described by Del Villar as "xero-siallitic soils." They are generally developed on acid rock detritus and, although leached, are not markedly podsolized. The natural vegetation was originally

forest, but is now *matorral*, a type of xerophilous scrub. Signs of erosion are everywhere evident. In the eastern part of the country, for example, in Aragon and Murcia, the soils are predominantly pedocalic with local development of saline and alkaline soils and, in the south, of terra rossa. Terra rossa occurs also near Lisbon. The black clays of Andalusia may be rendzinas and are reminiscent of the Houston Clay of Texas. Thin eroded mountain soils cover a large part of the country. Alluvial soils of great fertility occur in the coastal districts of Valencia. Probably no country of western Europe has suffered more than Spain from the deforestation of past centuries. The institution of measures for soil conservation and the right use of the national water resources are essential for the future of Spanish agriculture. Many of the red soils of Spain may be analogous to the red podsolic soils of the S.E. United States.

Balkan Peninsula. On account of the strong relief of this region there is generally a marked vertical zonation of soils. Brown earths, red soils resembling the nyirok soils of Hungary, and terra rossa are found in lowland regions, whilst podsolized and skeletal soils, including "karst" soils, occur at higher elevations. Black soils having some resemblance to the black prairie soils of Canada, have been described in the neighbourhood of Sofia. It would appear that considerable modifications have been produced by erosion, particularly in Greece, where the deep stoneless clays of the plains are sharply contrasted with the thin stony soils of the uplands. The tradition of a former cover of soil carrying forest in the uplands of Greece is mentioned in Plato's *Critias*. Steppe soils occur in northern Greece. The red soils, other than the terra rossas may be analogous to the red podsolic soils of the United States.

Russia. Modern conceptions of soil genesis have largely developed from the studies made on the soils of Russia. The dominance of Russian ideas in systematic pedology is the natural outcome of the co-ordinated efforts

of a national school of investigators having as its province the wide range of climatic conditions implied by the vast extent of the Russian Empire.

The succession of soil groups in European Russia is relatively simple. In the extreme north is the tundra region, succeeded to the south by a broad belt of podsoles which pass into the degraded chernozems or grey forest soils.

The boundary separating the grey forest soils from the chernozems runs roughly south-west to north-east, passing through the Ukraine. The chernozem zone is succeeded to the south-east by the chestnut-coloured earths, and these, in turn, pass with increasing aridity into the grey and brown semi-desert soils of the Caspian region. Saline and alkaline soils occur as local developments in the Caspian region.

ASIA

India. India may be divided broadly into three main regions, namely, the peninsula in the south, the Indo-Gangetic plain, and the Himalayan Highlands. The most salient feature of the soils of India is the large proportion of alluvium. The greater part of the Indo-Gangetic plain is occupied by the deposits of the Indus, Ganges, Brahmaputra, and their tributaries. Whilst recent alluvium cannot be expected to reflect the operation of the pedogenic processes consequent on the local climate, the older alluvia show varying degrees of maturity. There is thus a marked distinction between the soils developed under the semi-arid climate of the Punjab, and those developed in the more humid climate of Bengal. Soils with carbonate accumulation and soils of the saline and alkaline group occur in the former areas, but are absent from Bengal. A considerable area of desert and semi-desert occurs in Sind and Rajputana.

The southern or peninsular part of India is occupied partly by red soils and lateritic soils and partly by black cotton soils. Soils which may be analogous to the chestnut-coloured earths occur in Hyderabad to the east of the black cotton area.

The black cotton soils, termed *regur* in Central Provinces and Hyderabad, occupy an area lying to the east of the Western Ghats and including a large portion of these Provinces. The affinities of the black cotton soils with the black earths have been discussed in Chapter XI. Typically they are derived from trap rock—the so-called Deccan trap. The depth varies considerably: it may reach as much as twenty feet in areas of accumulation, but a depth of one to five feet is more usual.

When wet, the black cotton soils form a slimy colloidal mass, but on drying out they readily pulverize, so that the soil is said to “plough itself.” The published mechanical analyses of certain typical soils do not, however, show high proportions of clay, and the reason for their highly colloidal character requires investigation.

The development of the zone of carbonate accumulation varies somewhat and may in some cases be almost vestigial. It is possible that the black cotton soils may prove to have affinities with the rendzinas on the one hand and the vleis soils on the other, whilst an analogy with the Transvaal black turf soils may also be suggested. It is significant that in certain areas where black soils occur, the higher ground is occupied by red soils, which may stand in the same relationship to the black soils as the red limestone soils to the black limestone soils in Barbados.

The problem of the mode of origin of these soils and their position in a world classification still remains obscure. They are generally associated with trap as a parent material. Yet trap at higher levels can give rise to lateritic products. Further, black cotton soils can also occur on other parent materials. It seems evident then that they owe their origin to the conjunction of certain types of parent materials with certain topographical and climatic conditions, which have yet to be defined. Affinities with *teen-sudas* (p. 349) may exist.

Comparatively little information is available as to the red soils of southern India. Developed under a monsoon

climate and mainly derived by primary weathering from crystalline rocks, they are probably similar to the red loams and red earths of East Africa. Laterites are said to occur along the west coast, and in Bihar, Orissa, and Chota Nagpur.

The soils of the Himalayan Highlands show marked vertical zonation and include brown earths, podsolized soils, gley soils, and skeletal alpine soils.

Ceylon. The soils of Ceylon fall into five main groups, namely, (1) Tropical red soils, including lateritic and non-lateritic red loams and red earths, presumably similar to the red soils of southern India; (2) Red soils of the terra rossa type developed on limestone; (3) A group of soils known as "*patanas*," described as mountain steppe soils. They are sub-divided into dry and wet *patanas*, the latter occurring at higher elevations (<4,500 ft.). Both are acid in reaction and show a sesquioxidic type of clay. Their position in a world classification seems obscure. (4) Immature soils on Pleistocene and recent deposits; (5) Paddy soils with gley characters, and almost neutral reaction.

Siberia. In Glinka's "Typen der Bodënbildung" a soil map of the Russian Empire on the scale of 1:20,000,000 is given. The zonation of soil groups in Siberia follows generally the parallels of latitude, and the succession from north to south is from tundra through podsols, black earths, chestnut earths, to grey desert soils. The podsol region extends further south in the mountainous regions adjoining Thibet and China. Most of the area above 60°N latitude is tundra. Degraded chernozems, saline and related soils, and desert soils occur in Turkestan.

Asia Minor and Cyprus. Recent studies have shown the occurrence of terra rossa in Palestine. Comparatively little is known of the soils of Syria and Asiatic Turkey, but they probably include intermediate stages between the brown earths of Europe and the red soils of the tropics. In the drier regions, the black earth to chestnut earth succession probably occurs. Podsols and skeletal soils may be expected in mountainous regions. The soils of Cyprus

include terra rossa, red soils derived from igneous rocks, and steppe soils of pedocalic type.

China. Practically all the great groups and sub-groups with the exception of tundra are represented. A large part of the country has been under cultivation for many centuries and the soils are thus considerably modified. Erosion has played a considerable part. China proper may be divided into two main climatic regions, namely, the sub-humid, semi-arid and arid regions of the north and north-west, and the humid regions of central and southern China, and the eastern seaboard. In the former regions, pedocalic soils predominate, ranging from chernozems in varying degrees of maturity to the grey soils of the Gobi desert. Podzols occur in the north and in the south-west, whilst varieties of brown earths or brown forest soils and degraded chernozems are found in central and N.E. China. Red soils, probably akin to the tropical red loams and red earths, sometimes showing podsolization, are found in the south. There are large stretches of alluvium, which may be subdivided into calcaréous, non-calcareous and saline. Patches of saline and alkaline soils are also found. The rice (paddy) soils have been described as ground-water podzols. Deposit of æolian material from the loess is an important factor in the maintenance of fertility of cultivated Chinese soils.

Indo-China. Tropical red loams and lateritic red earths occur in Indo-China.

AFRICA

The soils of Africa lie almost entirely within the tropics and sub-tropics. Analogues with the soils of cool temperate regions are only to be expected in high elevations.

H. L. Shantz and C. F. Marbut, in a study of the vegetation and soils of the continent, have collected a considerable amount of information as to the principal types of soil and their distribution. The map, prepared by Marbut, may serve as a starting point, although it is certain that many

details and, possibly, some of the principal features of it may need modification.

The northern part of Africa is predominantly arid, a large proportion being actually occupied by the Sahara, Libyan, and Egyptian deserts. The soils of the Mediterranean seaboard include pedocals of the chestnut-coloured earth group passing through grey-brown desert soils to desert soils proper. In the wetter regions of the Atlas range, soils of the brown earth type may occur. South of the desert region the humidity increases and there is a transition through chestnut-coloured earths and chernozems to the humid tropical soils of Equatorial Africa. The African pedocals have been little studied except in the Sudan. The soils of the Sudan Gezira, which have been so thoroughly studied by A. F. Joseph and his collaborators at Khartum, appear to be grey-brown soils of the semi-desert, in which the profile has been considerably modified by circulation consequent on the formation of deep fissures during drought.

Pedocalic soils occur also in Kenya, Somaliland, Abyssinia, and Rhodesia. Marbut's classification of the Transvaal "black turf soils" as chernozems has been controverted by Marchand, and it is possible that equally intensive local study might necessitate further modifications in the provisional grouping suggested.

Saline and alkaline soils occur in association with the alluvial soils of the Nile delta and with the pedocalic soils of the Sudan. Swamp soils occur in many parts along the coast of W. Africa, notably in southern Nigeria.

The more humid parts of the continent are mainly occupied by red soils, which appear to show all gradations between red loams and ferrallitic soils. The latter group appears to be best developed in Sierra Leone, Liberia, and Ivory Coast. Laterites are also widespread.

French North Africa. Here the red Mediterranean soils are the best developed, but are often affected by erosion, which may have been catastrophic in consequence of excessive deforestation.

The lower hills and the plateau of Tell carry sometimes rendzinas, but are mainly occupied by calcareous crusts covered with reddish-chestnut soil. The latter are developed also on old alluvia of the lower plains, e.g., in Atlantic Morocco, the valley of Chelif, and the Plain of Tunis. In these areas, recent alluvia are only slightly developed, but are chemically rich and fertile under irrigation. Occasional patches of saline-alkaline soils may occur.

On afforested hills and mountains, soils vary rapidly with altitude from red Mediterranean soils to podsollic soils. Brown steppe soils and soils with crusts cover the high plateaux. Grey and red semi-desert soils occur in the transition to the Sahara, an immense desert with patches of saline soils, skeletal soils, and other typical desert forms.

Union of South Africa. The great complexity of the parent materials and the resultant configuration of the country caused by mountain barriers, which have a marked influence on the precipitation and other climatic factors, are directly responsible for the great diversity of the irregularly distributed soil types and groups. Topography and resultant climatic features are responsible for humid and sub-humid regions lying adjacent to semi-arid and arid regions, producing corresponding soils. The transitions are generally abrupt, the changes taking place within a distance of a few miles.

Although the soil distribution is irregular, well defined soil groups have, however, been developed. In some instances the parent material is the dominant soil-forming factor that determines soil development and in others again the climate and organic life are the "active" and geology the "passive" factors. Generally, the climatic factor dominates the parent material in the evolution of the soils.

In the arid region of the Union (Karoo), comprising the whole of the Cape Province except for the coastal strip, occur the desert soils, mainly derived from sedimentary rocks. Associated with them are the alkaline or "brak" soils, which have developed under local conditions.

Mechanical disintegration of the parent material, resulting from sudden and extreme temperature changes, predominates over all the other soil-forming factors.

To the north of the desert soils are the Kalahari Sands and Kalahari Sands on limestone. The latter are found on the outskirts of the former in Bechuanaland and South-West Africa.

East of the above-mentioned soil groups are the podsollic soils encircling the Basutoland Mountains and extending eastward to the Indian Ocean. Three stages of development have been observed. The more mature stage has been classified as gley-like podsollic soils.

In southern and central Transvaal and northern Natal have developed the reddish-brown and grey ferruginous lateritic soils. These soils are characterized by either an extremely hard ferruginous hardpan or a thick uncemented concretionary ferruginous layer. They are considered to be "ground-water" laterites.

In the central Transvaal occur the sub-tropical black clay soils, derived from basic igneous rocks—norite and basalt.

On the eastern escarpment of the Drakensberg and Zoutpansberg, running north-south from the Limpopo River to south of Natal, the rainfall and temperatures are very high and here soil groups, classified as laterites, lateritic red, and lateritic yellow earths have developed. These are not ground-water (Buchanan) laterites. To the east of these groups are found the brown forest soils, developed under high temperatures and relatively low rainfall.

The coastal strip of the Cape Province has podsollic and truncated podsollic soils developed from sandstone and shales respectively under winter-rainfall conditions. Skeletal soils are found in Basutoland and other mountainous regions, e.g., Cape Province and Transvaal.

Vlei soils are found in all parts of Africa, south of the Equator, and depend on local conditions of topography. Some examples have already been given in Chapter XIV.

French West Africa. The general distribution of soils is approximately in bands running roughly north and south parallel to the coast. The following is the general succession: sub-desert soils, brown soils, reddish-brown soils under thorn-steppe, leading to tropical ferruginous soils more or less bleached and showing concretions, at first under bush savanna and then under parkland (Senegal, Central and South Sudan, Upper Volta, and southern French Nigeria). Slightly lateritic soils occur under open forest; red soils and very deep grey laterites occur under dense forest.

Lateritic crusts, usually of a fossil character, extend widely between 10° and 13.5° north in the west and between 8° and 13° N. in the east. Generally speaking, they become indurated and develop only after destruction of the forest or bush by fire, followed by erosion of the superficial horizons. Such regions are almost sterile, particularly where the crust forms the surface of the soil.

AMERICA

United States. The great variety of climate, topography, and geology in the United States is reflected in its soils, which include representatives of nearly all the world groups with the exception of tundra and laterite.

The distribution of the main groups is shown in *Fig. 19*. The most important fact to be noted is the boundary line between the pedocals and the pedalfers (leached soils), which runs approximately north and south through Western Minnesota, Eastern Nebraska, Eastern Kansas, Mid-Oklahoma, and Mid-Texas.

To the immediate east of the great soil boundary from Minnesota to Northern Texas, lie the so-called prairie soils, most typically developed in Missouri. These are considered by the American workers to be a sub-group of the podsols, whilst European workers have considered them to be either meadow soils or degraded chernozems. Interspersed with the prairie soils are areas of meadow soils, as for example, in Iowa.

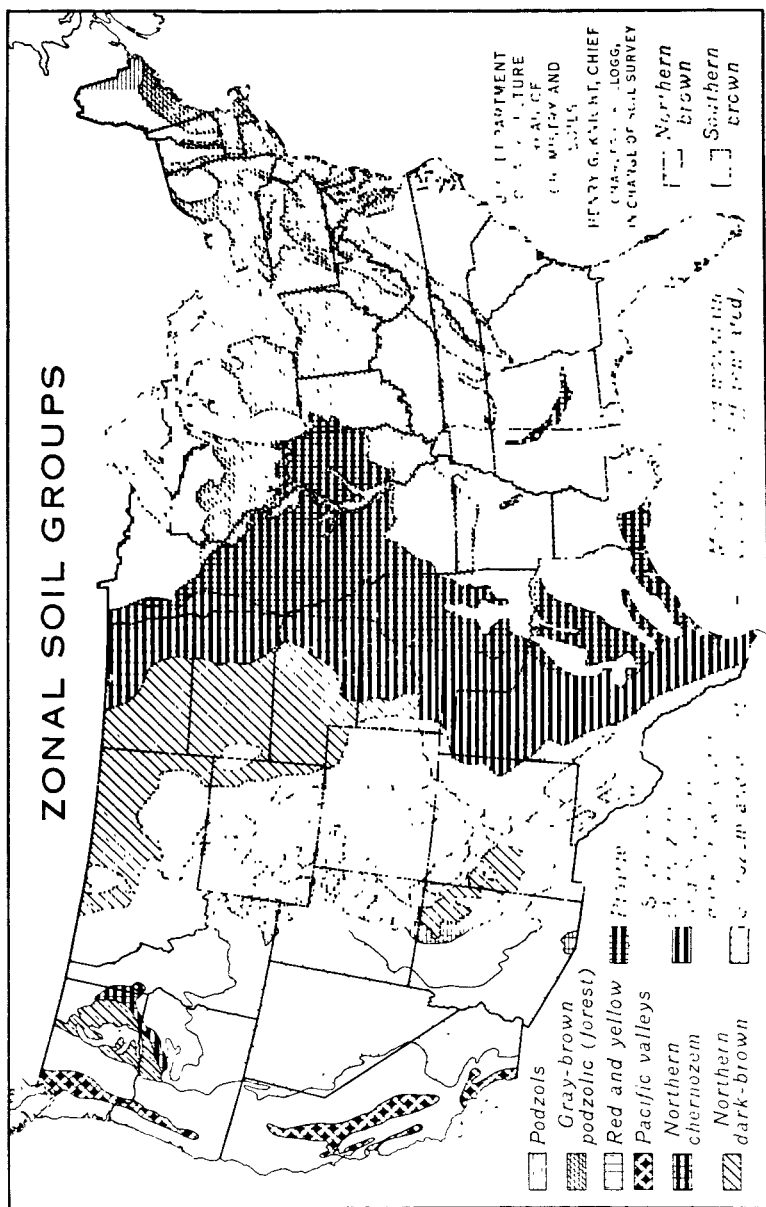


FIG. 10.—Great soil groups of the United States.

[After C. E. Kellogg.]

Podsols and brown podsollic soils in varying stages of maturity occupy most of the northern portion of the pedalfer region, including Eastern Minnesota, Wisconsin, Michigan, Northern New York, and the New England states.

The Middle-Eastern region is mainly occupied by grey-brown podsollic soils or brown earths, whilst the South-Eastern region from Virginia through the Carolinas, Georgia, Mississippi and Alabama, is mainly characterized by yellow and red podsollic soils with sub-tropical affinities. There are considerable areas of yellow soils in New Jersey and Maryland. These may form a transition between the brown earths and the sub-tropical red soils of the Southern States.

South of the 61°F isotherm in Alabama, and presumably also in Florida, the weathering is considered by L. D. Bayer and G. D. Scarseth to be of the lateritic type, but it is doubtful if laterite profiles, such as those of the tropics, characterized by superficial incrustations, are present. The relative enrichment of the upper horizons in sesquioxides by removal of silicic acid is, however, well established. It would probably be more correct to describe these soils as ferrallitic.

Large stretches of barren sands also occur in the South-East. These, presumably, exhibit podsolization. A considerable area of Florida is occupied by sub-tropical swamp soils. Alluvial soils, sometimes salinized, occur along the coast of the Gulf of Mexico.

West of the great boundary, increasing aridity is reflected in the successive belts of black earths and chestnut earths which pass in the northern region to grey desert soils with associated saline and alkaline soils. The latter groups attain their greatest development in Utah, Nevada, and Southern California. The southern desert soils are of the red and reddish-brown type.

Both in the mountain region and on the Pacific slope, are great areas of immature mountain soils. Brown earths, and, possibly, podsols occur in Oregon and Washington.

Canada. The soils of Eastern Canada adjacent to the United States are mainly podsollic, passing to tundra in more northern latitudes.

The course of the great soil boundary in Canada is somewhat indeterminate, but probably turns westward. Chernozems, prairie soils, and even podsoles occur in Manitoba, Saskatchewan, and Alberta. The grey wooded soils of Alberta and Saskatchewan are of particular interest because, although the profile is podsollic in character, they are often of fairly high base-status. Certain soils described as black prairie appear to belong to the meadow soil group. Saline soils occur in Alberta. Great areas of peat occur in the muskeg country of N. Ontario and the northern parts of the prairie provinces.

The soils of British Columbia are largely immature, but probably include brown earths and podsoles.

All the groups mentioned pass northwards into the tundra area.

Central America and West Indies. The most detailed study of the soils of these regions is the survey of the soils of Cuba by Bennett and Allison, to which reference has already been made at numerous points in this book. Whilst the general tendency, with the prevalence of humid conditions, is towards the production of a ferrallitic type of soil, all gradations can be observed from the well-known Nipe clay, which consists almost entirely of sesquioxides, to clays such as those of the Truffin and Bernal series in which a siliceous type of weathering complex is present.

Limestones give rise to two groups of soil. On the one hand are the mature leached red soils, exemplified by the Matanzas clay, which are essentially red earths; whilst the unleached limestone soils are represented by the dark-coloured plastic Bayamo clay.

Among the soils of Western Cuba are soils which closely resemble certain series encountered in the South-Eastern United States. They are found in coastal plain areas developed from out-wash material.

There are large areas of poorly drained soils which have affinities with meadow and vleis soils. In certain cases layers of ferruginous concretions or even hardpan (mocarrero) are developed. Soils with layers of carbonate accumulation occur, but it is doubtful if they are to be grouped with the pedocals.

In Cuba, as in other parts of the West Indies, there are considerable areas derived from coral limestone. Some islands, e.g., Barbados, consist almost entirely of coral limestone soils. The contrast between red and black limestone soils has been discussed in Chapter XV.

Many of the soils of the West Indies are very immature, whilst, in other cases, it seems likely that considerable erosion has taken place. There are extensive areas of clay soil in the Naparima district of Trinidad in which it would appear that the cultivated soil is only slightly modified from the parent geological material, which consists of marl or clay. Where maturity can be demonstrated, it is evident that the weathering is of a ferrallitic type. The most characteristic examples are seen in the weathering products of igneous rocks.

The soils of Central America, developed under humid tropical conditions, are generally similar to those of the West Indies, so far as can be judged. Pedocalic soils occur in Mexico, but have been little studied.

South America. Practically all the great soil groups are represented in this sub-continent which includes, tropical, sub-tropical, temperate, and cool-temperate regions. Large areas of alluvial soils occur in the basins of the Amazon, Orinoco, and La Plata. These have not at present been classified, but it is probable that they include considerable areas with developed profiles in addition to the juvenile soils on recent alluvia.

Tropical red soils, including red loams, ferrallites and laterites, occur both north and south of the Amazon basin. Pedocalic soils occur in Uruguay and the northern Argentine. Skeletal soils and podsolic soils occur in the extreme south

of the continent. Skeletal soils occur in the Andes-Cordillera region, with desert and semi-desert soils to the west in northern Chile, and red soils along the north-western seaboard.

Australia.—The Australian landscape is largely dominated by soils having recognizable counterparts in other continents. In some of these soils, climate has been the dominant factor in soil formation, in others parent material is co-dominant, whilst in others, the so-called fossil or senescent soils, are seen the results of soil profile development during Tertiary times.

The principal soils of the first or climatic category include: (1) high moor soils of the humid mountain areas in Tasmania, Victoria, and New South Wales; (2) podsoles differing from the classic podsoles in the minimal development of A_{00} and A_0 horizons and maximal development of A_1 horizons; (3) grey-brown, brown, and red podsollic soils with minimal development of A_{00} and A_0 horizons; (4) chernozem-like and tropical black soils; (5) red-brown earths similar to chestnut and reddish-chestnut soils in sub-humid areas; (6) heavy grey and brown pedocalic soils of semi-arid areas; (7) light textured brown and red-brown soils of semi-arid areas with weak pedocalic development; (8) brown and reddish-brown desert soils of the shrub-steppe desert margin, with calcium carbonate and, frequently, gypseous horizons; (9) red sandy and stony desert soils often with "pavement."

The climatic-lithological types include the following: (1) terra rossa on hard limestone; (2) brown solonized soils associated with loess and affected by cyclic salt; (3) red-brown calcareous desert soils on limestone; (4) rendzinas on soft limestone; (5) grey calcareous soils on soft limestone in semi-arid and arid regions; (6) solonchak-solonetz-soloti complexes occurring in southern Australia, where the accessions of cyclic salt are relatively high; (7) red loams of eastern Australia, ranging from Tasmania to tropical Queensland; generally deeply weathered and friable.

The "fossil" soils were developed in Tertiary times on a Pleocene peneplain now elevated to several hundred feet, truncated, and dissected. They are characterized by lateritic horizons, originally developed under the influence of ground-water, and show superficial podsolization. Truncation has generally removed the surface horizons leaving ferruginous crusts or concretionary material at the surface. By dissection the underlying kaolinitic weathering zone may be exposed and a new cycle of pedogenesis inaugurated leading to immature profiles.

Alluvial soils are of limited occurrence, but skeletal soils are common in the mountain regions.

New Zealand.—The soils of New Zealand have been divided into the following genetic groups: (1) Recent soils; (2) yellow-grey loams; (3) lowland tussock soils; (4) highland tussock soils; (5) podsols; (6) brown loams; (7) meadow soils; (8) peaty soils; (9) skeletal soils.

Recent soils occupying valley-bottoms are, except where stony or sandy, highly fertile. Yellow-grey loams occur in low rainfall districts in the North Island on parent materials high in lime and, although showing in places a grey A_2 horizon, are considered not to be podsols because of their high base content. Lowland tussock soils on the eastern lowlands of the South Island formed under tussock vegetation and low rainfall have a creamy yellow subsoil compacted into a clay-pan at eighteen inches below the surface. The highland tussock soils formed in intermontane basins and plateaux of the South Island under the same vegetation and rainfall as the lowland soils are grey-brown to yellow-brown in the subsoil. The soils of both these groups are little leached and are related to the podsol group. Podsols next to skeletal soils are the most abundant of North Island soils; in the South Island they occur chiefly on the West Coast. Two kinds are recognized, namely, (a) primary, on acidic volcanic ash deposits; and (b) secondary, on sedimentary beds.

The secondary podsols in the northern part of the North

Island and on the West Coast of the South Island show the deep A_2 horizon of the mature stage. In places in North Island the A_2 is cemented to a hardpan producing ground-water conditions. Brown loams covering large areas in the North Island are derived from andesite, basalt, and dolerite flows and ash deposits. They are friable soils of excellent physical condition, except in the mature stage of soils formed from basalt rock, which form compact subsoils containing "ironstone" nodules. The brown loams, which are of low silica-sesquioxide ratio are undergoing laterization. The meadow and acid-peaty soils of the tor lowlands, small in extent, have the usual characters of these groups. Skeletal soils on steep slopes—about thirty per cent. of the North Island and more than half of the South Island are shallow and closely related to the parent rock.

EAST INDIES

Our information concerning the soils of the East Indies relates principally to Java and Sumatra; but much of what may be said of the soils of these islands probably holds, *mutatis mutandis*, for the other islands.

Although Java and Sumatra are entirely within the tropics, generally under a monsoon climate, there is, nevertheless, a marked vertical zonation of soils from the tropical lowland soils to veritable alpine soils. Both sedimentary and igneous rocks occur, and there is, therefore, the possibility of great complexity in the resultant soils.

Most of the soils appear to be relatively juvenile, either through erosion, or else on account of their development from recent volcanic material. The effect of parent material is very marked, but the general tendency is towards the formation of red loams and red earths.

In Middle and Eastern Java, under a relatively dry climate, there are large areas of dark-coloured soils, some derived from igneous rocks, and others from marls and limestones, which appear to have resemblances to the black cotton soils of India.

Alluvial and swamp soils are of common occurrence in the coastal lowlands and may, in some areas, be of a peaty character. Here, as in the uplands, the character of the parent material is frequently of the highest significance in determining the properties of soils, particularly their behaviour under cultivation.

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*The references given here do not include all published works on the distribution of soils, nor, indeed, all the works consulted for the purpose of the above account. A fairly complete list is given, however, in the case of British soils since, in all probability, these will be of principal interest to the majority of readers.

Apart from the specific references given, a considerable body of information relating to soil cartography in many lands will be found in the volume of memoirs on soil cartography collected in 1924 by the late Professor G. Murgoi, of Bucharest, whose generous enthusiasm for the cartography of soils mainly inspired the co-operative efforts of the past decade, and, in particular, the production of the first Soil Map of Europe. Further information will be found in the volume of memoirs on soil nomenclature and classification collected by Professors H. Stremme and B. Aarnio in 1924. Finally, a considerable amount of information relative to the Russian Empire is to be found in the late Professor K. D. Glinka's "Typen der Bodenbildung." For the United States, abundant material may be found in the county soil survey reports published by the United States Soil Survey in co-operation with the different State Experimental Stations.

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CHAPTER XVIII

SOIL SURVEYS

AIMS AND METHODS

WHILST the aims of soil surveys are often mainly of an utilitarian character, work of this type is of great importance in elucidating the regional relationships of soils and the influence of climate and topography on soil genesis. Indeed, it is only by systematic mapping that the variations in soil characters within a region can be discovered and related together into a system, coherent in itself and capable of being placed in a wider system.

Soil surveys have been in progress for many years in different countries, but the organization of soil survey work has been developed more thoroughly than elsewhere in the United States of America in the form of a national soil survey under the Federal Government. In other countries, surveys have been made by workers at provincial institutions, or soil survey work has been included in the activities of the Geological Survey, as in Germany. In South Africa and Australia there are soil survey organizations specially devoted to irrigated and irrigable lands.

It is natural that, in different countries, there should be considerable variation in the aims and methods of soil surveys. To some extent, the degree of complication encountered in the distribution of soils will affect the methods chosen for their survey. The soil profile, the natural unit of study, is often so variable in its character, reflecting, as it does, changes in parent material, climate, and topography, that the execution of a complete record by mapping all relevant data may be a very slow procedure. On the other hand, there are areas even in Britain, where relatively simple

geology and topography under a uniform climate result in extensive tracts of soil which, if not actually constant in character, exhibit variations that can be easily related to topographical conditions.

We have already discussed the broad world classification of soils. In the present state of our knowledge, this classification is still imperfect owing to the insufficiency of existing information as to the soils of large areas of the globe. And, therefore, whilst it is possible, in countries whose soils have been minutely studied, to make direct use of some of the distinctions of a world classification for the purpose of primary study, in other countries the position of their soils in a world system is as yet so uncertain that it is not always possible to assign them to known groups. It is, indeed, certain that fuller knowledge of hitherto unexplored soil regions will add materially to our list of soil groups.

Whilst the survey of the soils of a new country should be carried out with careful attention to relationships with world groups, the first requisite is to obtain such a classification that the soils of the particular country will be thrown into the clearest possible relationship to each other. A valid classification of the soils of a given country is a necessary preliminary to their assignment to positions in a world system.

The scale of actual mapping varies considerably. In intensive surveys of highly cultivated areas, it may be necessary to map on as large a scale as 25 in. to the mile. For ordinary agricultural purposes in this country, a scale of 6 in. to the mile is more convenient. Smaller scales may be more useful for the rapid reconnaissance of large areas. The choice of a scale will, of course, be governed to some extent by the base maps available.

CHARACTER OF DATA COLLECTED

The character of the data collected in a soil survey will vary according to the amount of information already collected by other organizations. In Great Britain, much

information relevant to the soil is already recorded on the Ordnance Survey maps. Fairly detailed information about the geology is generally available, although in many cases the surface geology, which is of principal importance to the surveyor, is rather imperfectly described. In less settled countries, the amount of information available from other sources may be very scanty, and the surveyor is responsible for the collection of all data. In some countries, notably in the United States, aerial photography is used in the preparation of base maps.

From whatever sources they are obtained, the following data appear to be necessary for the characterization of soil conditions.

- A. Surface features.
- B. Parent material.
- C. Soil water conditions.
- D. Depth and succession of soil horizons down to parent material with data for each horizon as to :
 - a. Texture.
 - b. Structure and compaction.
 - c. Colour.
- E. Nature of cropping or vegetation.

A. Surface Features. Much of the information under this heading is already shown, so far as Great Britain is concerned, on the Ordnance maps used as base sheets. Where, however, contour lines are at wide intervals in gently undulating country, important surface features may be unrecorded on the base maps and should be shown on the soil map. It is convenient to distinguish a small number of categories for record. In Great Britain, for example, the distinctions, flat, rolling, steep, very steep, and broken or irregular are noted by appropriate symbols. Arrows are inscribed on the maps to show directions of slope. Special

symbols may be used to denote broken country, knolls, and depressions. The character of the micro-relief is often of great importance.

B. Parent Material. Here it is necessary to insist again on the distinction between parent material and parent rock. In some cases, as in the case of the deeply weathered layers often found in the tropics, the parent rock may be many feet below the surface and below the range of operation of pedogenic factors. In the case of glacial drifts and alluvia the parent rock may be remote and the period of weathering equally remote in time. In other cases the parent rock may itself be within the range of the pedogenic processes and may have an effect on the moisture régime and upon the growth of crops. This is the case with many shallow upland soils. In immature soils, the soil profile may consist entirely of slightly modified parent material without true soil horizons. This is the case in recent alluvial soils such as those of recent reclamations in Holland. There are also other instances in which the actual cultivated soil would appear to be almost unmodified parent material. These may be encountered in regions with rolling topography where erosion has removed the original soil horizons from unconsolidated parent materials. The agricultural soils in such cases are, pedologically speaking, C horizon material. The writer would assign certain sugar cane soils of the Naparima district of Trinidad and many of the Old Red Sandstone Marl soils of S. Wales and W. England to this class.

The soil profile is developed from more or less weathered rock and it is this weathered and, in some cases, transported material that forms the parent material of the soil. In some cases, as when a shallow soil is developed in decomposing rock, the rock may be thought to form the parent material. It is better, however, to bear the distinction in mind and regard the soil as being formed not directly from the original rock but from its weathered products.

It is often a matter of difficulty to decide the depth to which the soil horizons extend and the division must in some cases be arbitrary. Even in soils derived from material weathered *in situ*, there may be a thickness of weathered material overlying the parent rock which does not belong strictly to the soil profile, but which should be considered as parent material from which the soil profile has been differentiated. This is particularly the case in many tropical soils.

Although the basis of soil classification is the actual profile, it is convenient to be able to associate a particular soil with a given parent material and even with a given parent rock where the other pedogenic factors remain constant and the only variable is the parent material or the parent rock. The parent rock is not so much a definition of the soil as an indication where that soil may be expected to occur.

In classifying parent materials the lithology of the parent rock is of greater importance than stratigraphy. This means that it is necessary to take account of lithological variations in rocks of the same age. It means also that rocks of different age can be grouped together if they are lithologically similar. A classification of parent rocks is essentially lithological, but must also take into account conditions of weathering and transport.

C. Soil Water Conditions. Both from the standpoint of soil classification and of practical utility, distinctions under this head are of the greatest importance. It is convenient in the first place to distinguish soils of free drainage from soils with impeded drainage. The former may be subdivided into soils that are satisfactory and soils liable to drought. Soils with impeded drainage may be divided into soils with positional water-tables as in the valley bottoms or coastal regions, and soils of elevated regions having impervious strata. Varying degrees of wetness may be distinguished and, in addition, it should be noted whether wetness is continuous or intermittent.

It sometimes happens that excessive wetness may alternate with excessive dryness in the same soil. Changes in level of the water-table in a coarse sand may lead to such alternations. Further, in heavy clay soils, winter wetness may have the effect of restricting root development to the surface horizon. When drought occurs, the moisture within root range is quickly exhausted and capillary rise is too slow to repair the losses by evaporation and transpiration. These circumstances are generally reflected in the character of the natural vegetation or, in cultivated lands, the grass herbage. Indeed, natural vegetation or grass herbage are often the surest clues to the nature of the soil.

D. Depth and succession of soil horizons. The unit of soil study is the complete succession of horizons down to the parent material from which they have been differentiated. The soil survey should, therefore, include descriptions of all types of soil profile likely to be encountered. The data are conveniently recorded in notebooks with corresponding references to the field map. The actual description should be made from the examination of trenches or pits and uniformity of profile characters checked from point to point by auger borings. The actual depth of exploration will vary somewhat, but should reach to the full extent of the soil horizons. It is not generally necessary in Britain to go below three or four feet, but it is desirable to carry the examination to greater depths at intervals for confirmation. Profile exposures at quarry faces or gravel pits should be used with caution as they generally represent abnormal conditions.

The first step is to recognize the successive soil horizons, The approximate depth of each is recorded, together with data for texture, structure, and colour.

a. Texture. For some purposes, distinctions in texture are of great importance. For ordinary soil surveys, however, it is not practicable to have more textural grades than can be distinguished in the field by personal judg-

ment. In Great Britain, the following texture grades are recognized :—

Light Sand	...	...	...	...	Sa
Heavier Sand (or Loamy Sand)	...	...	...	...	Sb
Light Loam	...	...	...	...	La
Medium Loam	...	...	...	...	Lm
Heavy Loam	...	...	...	...	Lb
Clay	...	...	...	...	C
Coarse Silt	...	...	...	...	Za
Fine Silt	...	...	...	...	Zb

Intermediate grades may also be distinguished, such as sandy clay (Cs) and clayey sand (Sc).

In the United States, a much larger number of textural grades is recognized. The judgment as to texture obtained in the field is checked from time to time by actual mechanical analyses in the laboratory. With experienced surveyors, the correspondence is fairly close.

Special attention should be given to the presence of a texture profile.

b. Colour. Colour is perhaps the most difficult of all soil properties to describe accurately. Up to the present, no generally accepted scheme of colour description has been agreed upon. Such a scheme would be of considerable value, for there is, perhaps, no other soil property which is of such value for diagnostic purposes in the field. At present, the recognition and recording of colour distinctions is generally subjective and personal. It would be helpful to field workers if a select colour atlas were generally available for use in the field. The colours might be chosen to cover the range likely to occur in the field. Such a colour atlas is now actually in use in the United States Soil Survey.

The most important distinctions to be noted in soil surveying are between grey colours, on the one hand, and red and brown colours, on the other. Grey colours are found in arid soils, in the bleached layers of podsol soils, in soils with impeded drainage, and, in Britain and Northern France, in immature or eroded chalk soils. Brown and red colours are found in tropical soils and also in soils of temperate climates

formed with complete leaching in the absence of acid humus. Red colours may be conferred by the parent rock as in the soils of the Trias and Old Red Sandstone in England. Experienced surveyors can frequently detect the presence of admixtures of drift from the colours of soils. The presence of rusty-brown, orange, or yellow streaks or mottlings should be particularly noticed, since they are valuable evidence for the occurrence of waterlogging or drainage impedance.

c. Structure. This soil character has been given particular attention by Russian and American soil workers. In Britain, it has probably not been given sufficient importance. This may be due to the fact that British soils are generally moist, in which state structural characters are not so readily observed. Some of the typical structures recognized by workers in the United States are shown in *Plate III*. In addition to the macro-structure implied by the terms, granular, nut, platy, etc., it is desirable to consider also the micro-structure, noting the character of the small crumbs or fragments and such appearances as the presence of pores.

In connexion with structure, note should be made of changes in the degree of induration or compaction in the different horizons.

E. Natural Vegetation and Cropping. In a new country, a record of the natural vegetation is of the utmost importance, and may provide important clues to the distribution of soils. In difficult country, aerial photography has proved to be a convenient method of mapping vegetative cover if the aerial maps are compared with accurate ground surveys of selected areas.

In settled countries, the record of cropping at the time of survey is only of fugitive significance, but may be important in connexion with advisory work. In Great Britain, data on grass herbage are of considerable value both from the practical standpoint and also as an aid to the recognition of certain soil characters, more particularly the base-status and the moisture relationships.

Where possible, notes on weed and hedgerow flora should be made. Tree growth, also, can often be correlated with soil characters.

In the uncultivated lands of Wales, an exceedingly close correspondence is found between soil characters and vegetation type. By a view of the vegetation alone, it is frequently possible to obtain a fairly correct idea of the distribution of the different classes of soil.

G. R. Clarke¹ has summarized with explanatory notes the actual procedure followed in the field study of soils. The same author² has also prepared a Field Handbook and a form for the recording of profile data.

EFFECT OF SUPERFICIAL GEOLOGY AND TOPOGRAPHY

The problems confronting the soil surveyor will vary with the region to be surveyed. Whilst, in some areas, soil differences are easily seen, and the different classes recognized can be readily correlated with geology and topography, in other areas, the changes in soil character are so frequent that a trustworthy map can be produced only by the most minute examination. Complications, in such cases, generally reflect the intricacies of superficial geology. This obtains particularly over large areas of England and Wales, where the main task confronting the surveyor is the perception and delineation of glacial, colluvial, lacustrine, and alluvial deposits. Considerable help can often be obtained by an intelligent and imaginative interpretation of topography; yet there are also areas, such as certain alluvial and lacustrine flats, where the facts can be ascertained only by closely ranged auger examinations. In such cases, it may be impracticable to insert all the existing detail, but a close survey of specimen areas may serve to indicate the kind of variation to be expected over the area as a whole.

CLASSIFICATION INTO SERIES

A principal object in soil surveys is the production of soil maps in which the information gathered in the survey is shown pictorially. Unless the surveyor is to use the same

almost infinite range of colours used by an artist in painting a picture, he must have a limited number of categories for representation on his map. It may be, of course, that in thus limiting himself he is oversimplifying nature, but the error may not be serious if the limitations of soil maps are recognized and appreciated. For example, the clear, firm boundary lines of soil maps rarely occur in nature. At an early stage in the work, the soil surveyor must decide on his legend, i.e., the categories to be recognized and the colour or pattern by which they are to be represented on the map.

The arrangement into categories is based on the profile characteristics. Soils with similar profiles derived from similar material under similar conditions of development are conveniently grouped together as a *series*. A series is further sub-divided according to textural variations. In the United States of America, where this system is used in the Soil Survey, series are named after the localities where they are first studied or where they attain considerable development. The textural distinctions are shown in the *types*. Thus, the Leonardtown series include such types as the Leonardtown medium loam, the Leonardtown fine sandy loam, and so on. Finally, types may be subdivided into *phases*, depending on depth, slope, and degree of stoniness.

The series system with some adjustments has been adopted in Great Britain. In the early stages of the soil survey of Wales, it was found convenient to make a preliminary classification into *suites*, i.e., soils derived from the same or similar parent material. The qualification "or similar" was introduced because it was found that parent materials of different geological age, but of generally similar lithological character, give rise to the same type of soil profile under similar conditions of formation. The soils of a suite are divided into series according to the mode of development, as reflected in the profile. For example, the Powys suite comprises soils derived from weathered Cambrian, Ordovician, and Silurian non-calcareous hard sedimentary rocks,

excluding crystalline grits. The following series have, up to the present, been recognized :—

- (1) Powys Series. Well drained soils, developed from sedentary parent material on the parent rock.
- (2) Penrhyn Series. Well drained soils derived from glacial drift or colluvial material.
- (3) Cegin Series. Soils with impeded drainage derived from glacial drift or colluvial material.
- (4) Conway Series. Alluvial soils.
- (5) Hiraethog Series. Podsoles developed in sedentary parent material or drift.
- (6) Cymmer Series. Eroded soils resulting from the truncation of podsol profiles.

Each series gives types according to texture. Whilst, theoretically, a series might include a complete textural range, the variation is comparatively small in practice.

In the early stages of a survey, it is generally desirable to avoid too much restriction of the number of series. It is safest to assume, in the first instance, that distinct parent materials, even though lithologically similar, give rise to distinct soils. When, however, further study shows that the soils are indistinguishable, the series may be combined.

For example, in the author's experience, there is no essential difference between the soils from similar Cambrian, Ordovician, and Silurian sediments, and they are therefore grouped together. If it can be demonstrated that soils derived from Devonian or Carboniferous shales are essentially similar to these, then they also can be included in the larger group. The criterion is always the soil profile.

The *suite* as a higher category than the series was proposed by the present writer³. It was, perhaps, not entirely satisfactory because, at the time of its introduction, the distinction between parent material and parent rock was not sufficiently appreciated. More recently, other workers have proposed categories which, whilst yielding groups essen-

tially similar to suites, are more in accord with modern pedological doctrine. The most widely accepted grouping of soils for mapping purposes is the *catena* first proposed by G. Milne⁴ and further amplified by T. Bushnell⁵.

Milne's catena is essentially a group of soils derived from similar parent materials occurring in a complex in which the individual members are differentiated by topographical and hydrological conditions. For example, in E. Africa, there is often an alternation of red loams or red earths in elevated well drained sites with vlei or mbuga soils in depressed sites with seasonal drainage impedance.

The catena concept, apart from its value in directing attention to the relationships of different soils derived from similar parent material, is a convenient mapping unit in areas of great complexity so intricately arranged that detailed mapping would demand too great an expenditure of time and effort. Where catenas are mapped as units, it is necessary to work out the detailed distribution in a typical succession in order that the significance of *each* catena may be appreciated.

A similar concept to that of the catena is the *association*, introduced in Canada by J. H. Ellis and W. H. Shafer⁶, and used by R. Glentworth⁷ in the Soil Survey of Scotland.

In planning a soil survey, it is always a matter of difficulty to decide what degree of detail should be attempted. The standard scale in Great Britain is that of 6 inches to the mile, but for some purposes a scale of 25 inches to the mile might be desirable. Indeed there is scarcely any limit to the amount of detail that can be inserted, given sufficient time. In some areas of great complexity, a ten-acre field might occupy an experienced surveyor for many days if each small variation in depth, texture, slope, and moisture conditions were shown. At the other extreme is the temptation to produce soil maps quickly, partly to satisfy the demands of practical men and partly to impress those who distribute grants in aid.

In a country like Great Britain, a reasonable aim would be the production of maps covering the whole of the country on the scale of 1 inch to the mile without undue delay. In order to produce such maps it would be necessary to map sample areas in detail and then proceed with reconnaissance mapping on the scale of $2\frac{1}{2}$ inches or 1 inch to the mile over larger areas. In reconnaissance mapping, the unit might be the catena or association, but no area should be mapped as covered by a given catena unless the degree of complexity has been discovered and exemplified by the mapping of sample areas. The first soil map of the country would thus be a semi-reconnaissance map reinforced by well-distributed areas of detailed mapping.

Areas of mountain and waste present special difficulties. The base maps are generally lacking in detail, yet the actual soil pattern can often be exceedingly complicated. Here it might be sufficient to recognize a limited number of soil complexes and to illustrate them by detailed maps of sample areas.

An important part of a national soil survey is the correlation of the work of different surveyors. It is undesirable that the same soil series should be mapped under different names in different parts of the country; yet it is equally important that two series should not be assumed identical without careful comparison of the field and laboratory data. In the early stages of a survey, it is probably better to err by having too many than by having too few series. Frequent visits by surveyors to each other's areas are helpful.

THE USE OF LABORATORY DATA IN SURVEY WORK

The first appraisal of the soils of an area is, of course, made in the field and, in the opinion of some surveyors, soils should be mapped on field characteristics. Yet the identity of a given soil profile must rest ultimately on some securer basis than qualitative and personal judgement. It is therefore desirable that representative profiles should be submitted to careful laboratory examination and that the

series and type characters should be defined in a quantitative manner.

A complete definition of a series should give data on the following points:—

(1) *Mechanical composition of the principal types.* Whilst a certain textural range within the series is admissible, it is often the case that the mechanical composition curves show a general similarity that suggests their relationship. Mechanical analysis should always be used as a check on field estimates of texture.

(2) *Organic carbon and nitrogen content.* These figures will show some variation, yet the vertical variation of the organic carbon content within the profile may prove to be characteristic of a series. For example, soils with impeded drainage frequently show a sharp decrease in organic carbon content at the horizon of impedance.

(3) *The composition of the clay fraction.* Ideally this should be given by a determination of the relative proportions of the different clay minerals present, together with data, such as those given by the Tamm method for the more mobile constituents, in particular the iron oxides. The gross chemical composition of the clay fraction as expressed by the $\text{SiO}_2/\text{R}_2\text{O}_3$ and $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio, although less satisfactory, can often give useful indications and, in the absence of more significant data, should always be determined.

(4) *The base-status.* The variations in the base-status, as shown by the content of exchangeable bases or by the pH, are of great diagnostic value. In cultivated soils, however, liming may produce modifications, of which the surveyor should be aware.

(5) *The nature and distribution of soluble salts.* Whilst these do not occur to any marked extent in British soils, there are countries such as the Sudan, S. Africa, and Australia, where information on this point is of the greatest value in characterizing and classifying soils. Determination of exchangeable sodium may give valuable information.

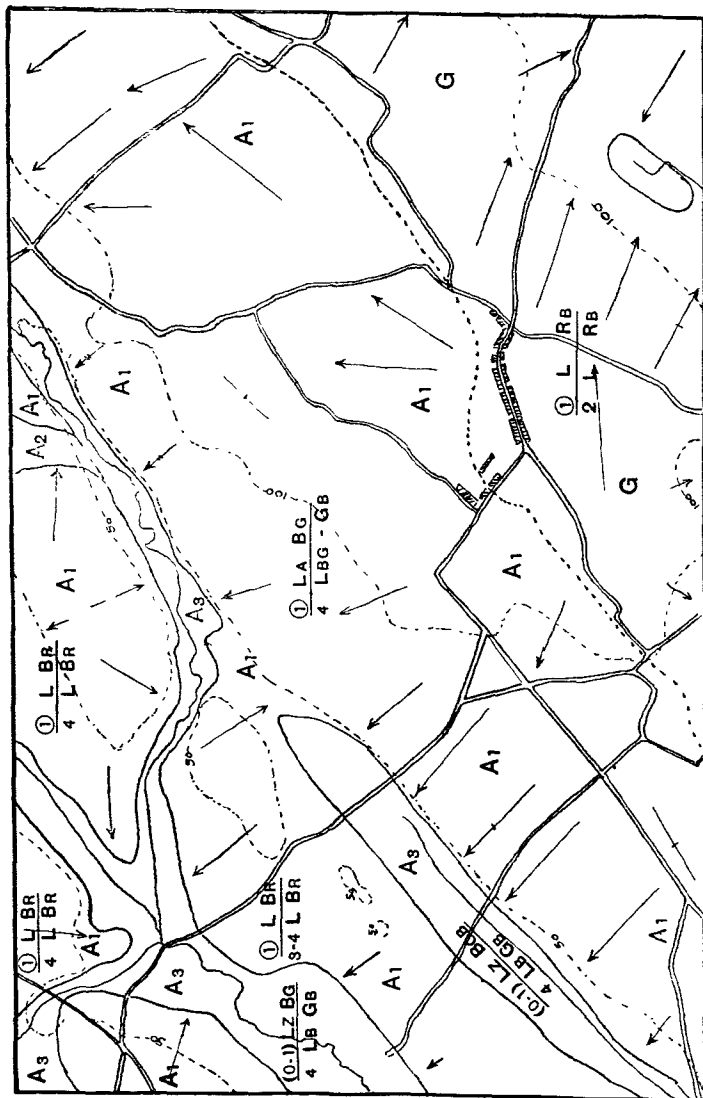
(6) *Mineralogical composition.* A knowledge of the unweathered minerals present in a soil is of great diagnostic value, provided the mineralogical composition of the parent material is also known. R. Hart⁸, in Scotland, has found the minerals of great assistance in identifying glacial drifts. Further, under tropical conditions, a knowledge of mineralogical composition may be useful in estimating the extent to which the soil has arrived at the end-point of its weathering. Unfortunately, available methods of analysis, in addition to being very laborious, do not succeed in giving a complete picture of the mineralogical composition of the soil, for they are not applicable to particles of finer grade than fine sand.

(7) *Physical properties.* It would be desirable to be able to express quantitatively those physical properties of a soil which affect its water-air relationships. Data showing the variation in pore-space throughout a profile would be exceedingly valuable as a measure of the degree of compaction. Unfortunately, the physical analysis of soils is at present in a less advanced stage of development than the mechanical and chemical analysis.

We have already alluded to the importance of obtaining a satisfactory scale for the expression of soil colours. When such a scale is available it would be desirable that colours should be recorded both for wet and dry soil, and after removal of humus by peroxide treatment.

SOIL MONOLITHS

In connexion with soil surveys in Russia and the United States, it has been found helpful to preserve records of the principal kinds of soil profile in the form of *soil monoliths*. These are actual columns of natural soil to the full depth of the profile. The taking of soil monoliths is an operation demanding considerable ingenuity. Essentially, the procedure consists in excavating a pit to the full depth of the soil profile and, after cutting away three sides of the proposed monolith, fitting a stout box. When the monolith



Surveyed by D. O. Hughes, J. O. Jones and Brynmor Jones.

FIG. 20.—Portion of six-inch soil map of Anglesey, XXII N.E.

(From "Journal of the Ministry of Agriculture"—by permission.)

Series A1. Gaerwen loam to light loam, deep, well drained soils derived from metamorphic schists. A2. Gesall heavy loam, soils derived from schistose material with impeded drainage. A3. Braint silty loam; alluvial soils from schistose material. G. Gower loam; rather shallow, well drained soils derived from Carboniferous Limestone. The arrows point down slopes.

fits snugly in the box, the fourth side is then cut away. The cut face is then chipped to obliterate spade marks and to throw up as far as possible the natural structure. The greatest difficulty is experienced in stony soils.

As a substitute for monoliths it has been proposed to apply a flexible material covered with an adhesive substance, such as glue, to a profile face. When adhesion is attained, the material is pulled away with the adhering soil.

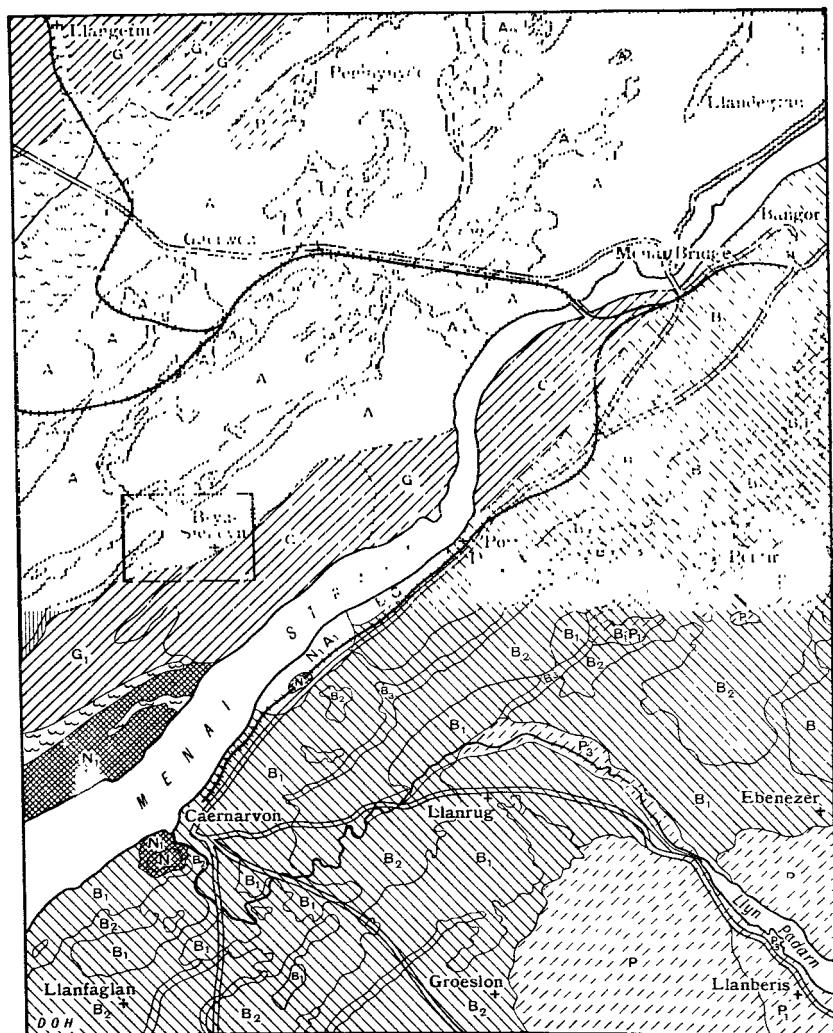
PREPARATION OF MAPS

In soil survey work in Great Britain, the Ordnance Survey map on the scale of six inches to the mile proves the most convenient base map for use in the field. On it should be recorded all data which can be conveniently inserted without undue crowding. In complicated areas, however, it may be desirable to insert key-letters or numbers referring to descriptions made in a field note book. Boundaries between soil series should be drawn in the field.

It is, perhaps, a matter for debate whether type boundaries should always be inserted. Generally speaking, the textural range within a soil series is not wide, and the delineation of fine textural distinctions may involve an amount of labour incommensurate with the value of the information given. In such cases it should be sufficient to insert textural data (La, Lb, etc.) at frequent intervals over the extent of each series on the map. In intensively cultivated areas, textural details may be of sufficient importance to warrant their close study and accurate delineation.

An example of a completed soil map of a part of Anglesey on the scale of six inches to a mile is shown in *Fig. 20*. The reproduction, for publication, of six-inch soil maps would generally be rather too expensive and they should be regarded mainly as the repositories of the information gathered in the field work.

For ordinary publication it is desirable to make a generalized map on the scale of one mile to the inch. Such a map would simply show the soil series and would not ordinarily carry detailed information as to textural varia-



Surveyed by D.O. Hughes, J.O. Jones, Brynmor Jones, and W.B.D. Walters.

Emery Walker Ltd.

0 1 2 3 4 Miles

- ANGLESEY SUITE:** A₁, Gaerwen; A₂, Gesail; A₃, Brant
BANGOR SUITE: B, Bangor; B₁, Ebenezer; B₂, Sion; B₃, Glanadda
GOWER SUITE: G, Gower; G₁, Pentraeth. **NEATH SUITE:** N, Neath; N₁, Ilston.
POWYS SUITE: P, Powys; P₁, Penrhyn; P₂, Cegin; P₃, Conway
Estuarine Alluvium.

FIG. 21.—Soil series map of portions of Anglesey and Caernarvon.

tions within the series; nor would it be practicable to show on such maps the minor topographical details shown on the six-inch maps. An example of such a generalized map is shown in *Fig. 21*, in which the area shown in *Fig. 20* is indicated by the small rectangle. It should be added that both maps have been further reduced for reproduction; but the difference in the amount of detail shown will be evident.*

LAND CLASSIFICATION

By this term is understood any type of classification that distinguishes land according to its use or potentialities. Whilst in a soil survey or a vegetation survey, the objective is simply the recording of physical facts, in a land classification an attempt is made to go a stage further and to draw certain conclusions from the physical facts taken in relationship to any other relevant non-physical factors such as economic conditions, sociology, and the like.

A very common type of land classification is according to "use-capabilities," and C. E. Kellogg² defines this as "one in which bodies of land are classified (on the basis of physical, or upon the basis of both physical and economic considerations) according to their capabilities for man's use, with sufficient detail of categorical definition and cartographic expression to indicate those differences significant to man."

Now whilst physical facts relating to soil, topography, and climate are objective and ascertainable even although there may be different methods of arranging the observed data, when land use and potentialities have to be considered, the resulting classification contains a large subjective element and is not purely scientific. For example, all experienced pedologists might agree that a certain soil is a grey-brown podsollic light loam and might agree as to its depth, slope, and moisture conditions. It would not be so

*NOTE.—Since the execution of these maps the Anglesey suite has been merged in the Bangor suite. The former Gaerwen and Ebenezer series become the Arvon series, the former Geail and Sion series become the Eivion series, and the former Braint and Glanadda series become the Ynys series.

equally evident that this soil is suited to a particular type of agricultural use. Even in the apparently simple task of classifying soils according to their productivity there is ample latitude for difference of opinion, according to the meaning to the assigned to the term productivity. And therefore, although for some purposes it may be permissible to prepare maps showing land set out in different categories of land use or potentiality, it should be realized that such maps have much less objective value than well executed geological or soil maps.

Land classification maps should be designed to answer specific questions. The more general the question, the less accurate is the map likely to be. For example, for some purposes there may be a demand for maps showing the different agricultural values of land. Such a map in its simplest form would show, perhaps, all the area divided up into good, medium, and poor land. The object of such a map might be to serve as a guide to planners who wish to avoid the diversion of the best agricultural land to urban or industrial use. Unfortunately, there is no clear and unambiguous definition of agricultural value or even of soil fertility, and the map produced must depend on a personal interpretation of the effect of the known physical factors.

With more clearly defined objectives greater significance is possible. For example, it might be possible to attain a fair degree of significance in maps showing liability to erosion or suitability for the growth of particular crops such as potatoes or market garden crops.

In spite of the difficulties of integrating all the site and profile characters of a soil to give a single index of productivity or fertility many schemes have been proposed for solving this problem. An early example of this is R. E. Storie's¹⁰ index, developed in California. Storie uses three groups of factors, namely, (1) general profile characters, (2) texture, and (3) conditions such as drainage, acidity, salinity, etc., modifying the productivity of the soil. A mark is assigned to each of the three groups of factors expressing

a percentage of optimum. The three are then multiplied together and expressed as a percentage of the maximum. This is claimed to give a fairer appraisal than addition, but it should be noted that the multiplication together of three moderate percentages, e.g., 70%, will give the very low final figure of 34%.

More usually, land is arranged into groups according to increasing or decreasing agricultural value. An example of this is the classification devised by L. D. Stamp¹¹ for the Land Utilization Survey of England and Wales. In this system, land is divided into 10 major categories, which are grouped into Good (4 categories), Medium (2 categories), and Poor (4 categories). The categories within the groups are based on qualitative distinctions such as suitability for grass or arable. A Committee of the West Midland Group for Post-War Reconstruction and Planning¹² devised a modification of this system, whereby the three groups were defined in terms of soil and site characters. The major categories are thus defined:—

Good quality land.—Highly productive under good management. Land in this category has the following characteristics:—

- | | | |
|------|---|---|
| Site | { | Not too elevated, level, gently sloping, or undulating. Favourable aspect. |
| Soil | { | Deep, with favourable water conditions (actual or potential).
Texture—mostly loams, but including some peats, sands, silts, and clays. |

Medium quality land.—Land of only medium productivity even under good management. Productivity limited by reason of unfavourable operation of one or more of the factors of site or soil character, e.g., by reason of—

- | | | |
|------|---|---|
| Site | { | High elevation.
Steepness.
Unfavourable aspect. |
| Soil | { | Shallowness.
Defective water conditions. |

Poor quality land.—Land of low productivity by the extreme operation of one or more factors of site and soil.

Another approach to the problem of land classification has been through "productivity ratings" based on observed performance of crops and grassland. The method is based on the work of J. K. Ableiter¹³. In the county reports of the United States Soil Survey, figures are given for each type showing the percentage of the "standard" yield obtained for each crop under (A) average farming and (B) the best type of husbandry. The productivity grade for a given soil is obtained by weighing the percentage yields according to the regional importance of the crops. Soils with a weighted percentage of over 90 are rated as Class I., those between 80 and 90 as Class II., and so on. The difference between the A and B ratings gives a measure of the response to good husbandry.

The problem of land classification transgresses the boundaries of soil science and enters the domains of economics and sociology, where facts are ascertainable with much less precision than in the natural sciences. Probably the best service that the soil surveyor can render to the would-be planners is to provide accurate soil maps and clear explanations of their significance.

G. V. Jacks¹⁴ has recently summarized the present state of the problem of land classification. The reader may be further referred to the Proceedings of the 1st National Conference on Land Classification (1940), published as Bulletin 421 of the University of Missouri under the title "The Classification of Land."

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CHAPTER XIX

SOIL ANALYSIS

INTRODUCTORY*

THE general purpose of soil analysis is to give a quantitative expression of the constitution and properties of the soil. It is complementary to the description of the morphology of soil in the field in that it gives greater precision to the specification of certain properties such as texture and reaction ; it is also supplementary in that it reveals and expresses certain properties, such as the composition of the clay fraction that cannot be estimated in a field examination.

Soil analysis is essentially the laboratory examination of soils as distinct from the field examination. It is true, of course, that soil analysis has been carried into the field by certain methods of rapid examination, yet such methods are generally only rough improvizations, except in those cases where, as for example in soil moisture studies, the essence of the method consists in its being carried out under field conditions.

Considering soil analysis as ordinarily practised, we may distinguish two distinct aims. Firstly, there is the practical aim of discovering and assessing plant nutrient deficiencies with a view to making recommendations on the manuring of crops. Under this head we may include the examination of the soil to discover the presence of constituents harmful to plant growth. To the practical man this is what is usually understood by soil analysis, and the num-

*The purpose of the present chapter is to discuss the significance of soil analysis. For details of actual methods the reader is referred to C. H. Wright, *Soil Analysis*, Murby and Co., London.

ber of analyses made annually in Great Britain for advisory purposes runs into tens of thousands. Soil analysis, or as it is more usually called, soil testing, is thus an important factor in British agriculture and, indeed, of the agriculture of all progressive countries. Just as in a modern industrial plant there is laboratory control at each stage, so in a modern farm manurial practice should, ideally, be based on the regular testing of each field.

There is, however, another purpose in soil analysis, namely, the exact and quantitative specification of a soil for the purpose of ascertaining its constitution and of comparing it with other soils. This purpose is primarily scientific and underlies all attempts to understand the genesis of soils and to arrange them in an ordered classification. The data obtained by this type of soil analysis are above all necessary to supplement descriptions of soil profiles in the field, which otherwise run the danger of becoming too qualitative and subjective. It is with this aspect of soil analysis that we shall be mainly concerned in the present chapter.

In considering methods of soil analysis, we may distinguish between *absolute* and *conventional* methods. In an absolute method, a determination is made of the total amount of a given constituent present in the soil, or of the amount falling in a definite category of the soil. The determination of the total nitrogen content of the soil is an absolute determination, as is also the determination of the ammoniacal nitrogen content. Similarly we may characterize the determinations of exchangeable bases as absolute determinations. Wherever it is possible to distinguish categories of constituents in the soil, the natural corollary is an absolute method of determination.

On the other hand, we have conventional methods. Many of the methods used in advisory work are of this type. They are generally the outcome of practical requirements and are of slight significance apart from their practical utility. In the determination of "available" phosphoric acid by the citric acid extraction method, it is necessary to

prescribe every detail of working; for any variation, for example, in the ratio of solvent to soil, or in the time of extraction, may lead to different figures being obtained. The phosphoric acid thus determined does not represent any category of soil phosphorus that can be defined in terms other than those of the method by which it is obtained. Methods such as these can have only a temporary value and must be superseded when fuller knowledge of the constitution of the soil enables us to distinguish and determine the different categories of soil constituents.

From the standpoint of the study of the soil as a pure science, the chief end of soil analysis is to characterize the material with which it deals. An ideal system of soil analysis should give a complete quantitative description that will serve as a basis for comparison and classification. The need for such a system of analysis is abundantly evident when we consider the qualitative terms in which many of the most important groups of soils have been described. The task of soil classification cannot be considered complete until these subjective descriptions have been translated into definite quantitative data. Such data are as important as the physical and chemical data necessary for the description of chemical compounds.

MECHANICAL COMPOSITION

The first information required about a soil is its mechanical composition. The practical man, confronted with a soil, will always wish to know whether it is a clay, a loam, or a sand, and the pedologist will seek the same information expressed in quantitative terms. Mechanical composition gives quantitative expression to a fundamental property of soil, unaffected by the ordinary vicissitudes of cultivation and cropping. The results of mechanical analysis can be most readily interpreted when shown in the form of a summation curve, for, as we have seen in Chapter II, different types of soil give characteristic curves. Thus, there are characteristic curves for highly weathered soils, for

mechanically weathered soils, for alluvial soils, and for soils of mixed origin.

Mechanical analysis is of particular value in controlling field estimates of texture. It should be noted, however, that mechanical composition is a property of the soil which, although closely correlated with texture, is quite distinct from it. Texture relates to the physical properties of the soil under cultivation and is essentially a property that obtrudes itself on the tiller of the soil. With soils having the same general mineralogical composition and organic matter status, mechanical composition reflects texture fairly closely, so that the concordance between field judgement and laboratory data may be very satisfactory. The character of the clay itself affects the texture; with highly sesquioxidic soils such as occur in the tropics, the tendency is to under-estimate the clay content.

The most important single figure in mechanical analysis is the clay content. If the clay fraction has been appropriately defined, it enables us to state what proportion of a given soil consists of the reactive colloidal products of chemical weathering, as distinct from the unweathered material, which is relatively inert and acts simply as a framework or skeleton for the reactive constituents.

IGNITION LOSS

The loss in weight suffered by an oven-dry soil on ignition was formerly used as a measure of the proportion of organic matter present. It was always realized, in the case of soils containing much clay or calcium carbonate, that the results were likely to be of little value, and even with lighter soils, small amounts of organic matter cannot be shown by ignition loss. Recently, however, this determination has acquired new importance, for B. A. Keen and P. R. H. Coutts¹ have shown that it does afford an approximate indication of the colloidality of the soil and is highly correlated with the "sticky point" value. G. J. Bouyoucos² has proposed a method for determining the combined water of soils by distillation. This procedure offers considerable promise

since by subtraction from the ignition loss of the figure thus obtained it is possible to make an estimate of organic matter.

CALCIUM CARBONATE

Calcium carbonate is usually determined and shown with the mechanical analysis of a soil. The presence of calcium carbonate, except where it occurs as comparatively coarse isolated fragments, indicates base-saturation and, in natural mature profiles, is characteristic of certain horizons of soils of the chernozem and chestnut earth group. Calcium carbonate may also occur, under certain circumstances, in horizons affected with ground-water. Among immature soils, the rendzinas are characterized by the presence of free calcium carbonate as, for example, in the chalk soils of South-East England and Northern France. In soils of the humid regions—the “pedalfers” of Marbut—calcium carbonate is only a fugitive constituent and does not occur in mature profiles.

ORGANIC MATTER

Of equal importance with mechanical composition is a knowledge of the organic matter content of the soil. The greater proportion of soil organic matter consists of colloidal material, which, with the clay, forms the colloidal complex. The organic matter is also the seat of micro-biological changes in the soil. It is obvious, therefore, that a knowledge of the amount of this constituent is of the highest value in characterizing a soil. Its direct determination has hitherto been a matter of some difficulty, although the method of Bouyoucos, to which reference has been made above, appears to offer possibilities. It is more usual to obtain a measure of it from the determination of organic carbon, using a conventional factor (1.724) to convert to organic matter. The organic carbon is determined by dry combustion or by wet combustion methods. In cultivated soils, it is sometimes necessary to make a correction for elementary carbon in the form of coal or cinder.

The determination of the organic matter content is only the first approach to a characterization of the organic portion of the soil. There are obvious differences between 5% of organic matter in a typical red loam, a black earth, and a podsol, respectively. It is, therefore, desirable to have methods for the fractionation of organic matter. Various methods have been proposed, such as the determination of humified organic matter by hydrogen peroxide, and the determination of pentosans, lignins, and celluloses; but, until the proposed methods have been investigated over a wider range of soils, the significance of the results yielded by them is not sufficiently evident for their adoption in routine analysis. It is probable, however, that investigations now in progress will eventually lead to the recognition of methods for the characterization of organic matter that will be of the highest value in soil classification.

NITROGEN

The determination of nitrogen is often made without any clear idea as to its significance. For purely practical purposes, it can rarely serve as a measure of the nitrogen status of the soil. As a measure of soil organic matter, it is highly untrustworthy because of the great variation in the nitrogen content of organic matter. In recent years, a considerable amount of work has been carried out on the carbon-nitrogen ratio of soils, and, whilst the significance of this ratio is not completely understood, some of the indications are sufficiently suggestive to render it highly desirable that it should be determined over as wide a range of soils as possible. It may yet prove a valuable aid to the definition of soil groups.

The significance of the ammoniacal nitrogen content of soils is not sufficiently evident to recommend its general determination. Except in acid organic soils, it is generally present in very small proportions. The nitrate nitrogen varies so greatly in amount in the same soil that it can scarcely be used as an aid to description.

TOTAL ANALYSIS

In a perusal of the literature of the subject, the student will find numerous descriptions of soils and soil profiles in which the complete analysis of the total soil is given. Such analyses, involving the determination of silica, sesquioxides, titanium oxide, alkalies, and alkaline earths, represent a very considerable mass of effort, yet the value of the information to be derived from them is, in the writer's opinion, of an entirely lower order of magnitude, since they fail to distinguish between the unweathered minerals and the weathering complex. They may be compared with results of analyses of entire animals made by the pioneers in animal nutrition. Total analysis may find some use in connexion with methods for estimating the degree of weathering of soils.

EXAMINATION OF THE CLAY FRACTION

So far as the mineral portion of the soil is concerned, the clay fraction is the seat of most of its chemical reactivity. Further, it is in most soils approximately identical with the weathering complex. For these reasons, its specification is of the highest importance. For many years it has been customary to express the composition of the clay by the molecular ratios $\text{SiO}_2 : \text{Al}_2\text{O}_3$, $\text{SiO}_2 : \text{R}_2\text{O}_3$, and $\text{Al}_2\text{O}_3 : \text{Fe}_2\text{O}_3$. Whilst the information given by these ratios sheds considerable light on the nature of the clay and on the trend of profile development, it has long been realized that the information thus given is far from adequate to specify the clay constituent. During recent years, considerable progress has been made in X-ray analysis and it is now possible to indicate the approximate proportions of the different types of clay minerals present.

Valuable as this information is, however, the specification of the clay complex is incomplete unless it includes also the necessary data about the non-crystalline constituents, in particular iron and aluminium oxides and free silicic acid.

It is this kind of information that is given by the method of O. Tamm³. Other methods are also available, including those of M. Drosdoff and E. Truog⁴ and of H. G. Dion⁵ for determining free iron. The value of these methods is that they give an insight into the character of the mobile or active colloidal material in the soil and may therefore provide a more sensitive index of eluviation and illuviation than total clay analyses or mineralogical data. The development and use of these methods can, therefore, be strongly recommended.

EXCHANGEABLE BASES

The properties of soils are, as we have already seen, so strongly affected by the nature and amount of the exchangeable bases present that any description of soil must include data for these constituents. For most soils of the humid regions, about 80% of the reaction value of the total bases, exclusive of hydrogen, is represented by exchangeable calcium, and therefore it is generally sufficient to determine only this base. In saline and alkaline soils, however, exchangeable sodium forms a considerable if not principal proportion of the exchangeable bases, with or without free sodium salts. The determination of exchangeable bases in soils containing notable amounts of free calcium carbonate is generally unnecessary, except in saline and alkaline soils, but may be carried out on typical samples.

In most soils, calcium is the dominant exchangeable base, and a determination of exchangeable calcium gives a fair measure of the total exchangeable bases present. For more accurate work, it is often desirable to determine the other bases and also the reaction value of the sum of the exchangeable bases. Where this value is reached by summation of separate determinations, it is usually somewhat magnified by the inclusion of soluble salts, principally calcium sulphate and chloride. This is avoided in the acetic acid method of R. Williams⁷.

REACTION

The reaction of soils, generally expressed as pH, the negative logarithm of the hydrogen-ion concentration, has been the subject of a large amount of investigation. Before discussing its significance, it is necessary to direct attention to the somewhat conventional and arbitrary character of the results obtained. When we speak of the pH of a soil, we cannot achieve a precise significance unless the conditions of determination are exactly stated. The pH of a dry soil would be meaningless, since active hydrogen-ions can only exist in solution. Determinations of pH therefore refer to soil-water pastes or suspensions and, since different results can be obtained according to the soil-water ratio used, it is necessary to specify the actual ratio. It has been recommended by the International Society of Soil Science that a soil-water ratio of 1 : 2.5 should be used, but it should be clearly realized that, even where this recommendation is followed, the results are only of comparative value and are no absolute measure of a soil property.

It should be noted that the reaction of a suspension of a soil, even under standardized conditions of determination, is governed not only by the degree of saturation of the complex acids of the colloidal complex, but also by the nature of the complex itself. Broadly speaking, the greater the ratio of the acidoid groups, silicic acid and humic acid, to the basoid groups, aluminium oxide and ferric oxide, the more acid will be the reaction at a given degree of saturation. A lateritic soil may contain very small amounts of exchangeable bases and yet show a pH approaching neutrality, whilst a soil rich in organic matter or with a highly siliceous clay complex might show a pH of 4 or even less at the same degree of saturation. Low pH values may also be due to the presence of mineral acids.

In spite of these limitations, pH data do give an indication of the relative base-status of similar soils and are of significance in connexion with many of the most important pedogenic processes. The lowest figures are found in

peats and humus podsoles, whilst the highest figures are found in alkaline soils. Red podsollic soils, red loams, brown forest soils, and black earths, occupy intermediate positions.

CONSTITUENTS SOLUBLE IN STRONG ACIDS

Proceeding from the assumption that regulated extraction with strong mineral acids can separate the weathering complex of the soil from the unweathered portion, many investigators determine the amounts of silica, alumina, ferric oxide, and other bases soluble in hydrochloric or sulphuric acid under conventional conditions of working. In the writer's opinion, however, there is no evidence that any acid extraction can succeed in dissolving the weathering complex without attacking unweathered minerals in addition. Nevertheless, the results obtained by such methods may afford indications which may be of practical value as to the reserves of plant nutrients in the soil. Phosphoric acid is frequently determined in acid extracts, but no evidence is yet available that the amount thus brought into solution represents any definable category of the phosphorus compounds of the soil.

SOLUBLE SALTS

In certain classes of soils, it is desirable to make determinations of the content of soluble salts. As a complete analysis of the soluble salts is generally a tedious operation, it is often considered sufficient to obtain an indirect estimate by determining the electrical conductivity of aqueous suspensions.

PHYSICAL DETERMINATIONS

An account of soil analysis would be incomplete without some reference to the use of physical determinations for the description and definition of soils. But, apart from mechanical analysis, which is essentially a physical determination, it must be admitted that methods are still in process of evolution, and that no generally accepted system of physical determinations exists. It may be helpful, however,

to review briefly those physical properties of the soil which, from the standpoint of soil definition, call for quantitative expression.

PORE-SPACE AND VOLUME WEIGHT

A knowledge of the variations in pore-space and volume weight throughout the soil profile would doubtless be of considerable aid to the definition of the principal soil groups. But whilst the determination of pore-space and weight per unit volume offer no difficulty with laboratory samples, determinations under field conditions are laborious and, except in almost stoneless soils, beset with considerable experimental difficulties. In spite of the importance of the information sought, it must be admitted that the determination of pore-space has not yet become one of the routine investigations of the soil worker.

SINGLE-VALUE DETERMINATIONS

In recent years, attempts have been made to express those properties of the soil associated with their colloidal character by means of so-called "single-value" figures. Of those which may more properly be called physical determinations, hygroscopicity, moisture content at the "sticky point," and heat of wetting, have been most widely used.

Whilst the earlier workers on hygroscopicity attempted to determine full hygroscopicity in equilibrium with a saturated atmosphere, recent workers use atmospheres below saturation point. There is, at present, no uniformity of procedure.

The determination of the moisture content at the "sticky point" has, in recent years, attained considerable vogue among British workers, and since it does appear to have a definite physical meaning, i.e., the moisture content at which the soil gels are completely saturated, it should prove of great value in defining and describing soils. As it is determined with comparatively little labour and expense, it may be recommended for routine workers and will doubt-

less prove of increasing value as results are accumulated and examined in relation to other soil properties.

Heat of wetting has been used by certain American and continental workers, but has not come into general routine practice.

COLOUR DETERMINATION

The colour of soils is an important aid in the recognition of the soil groups. Such groups as laterites, terra rossa, podsols, and black earths, have colours which are highly characteristic. These are almost invariably described in qualitative terms, with the result that, whilst a worker familiar with podsols has a clear idea of the range of colours met with in these soils, his descriptions will not convey an accurate impression to a worker familiar with tropical soils who may, indeed, use similar terms to describe unmistakably different colours.

The American soil survey workers have made efforts to define soil colours by methods such as the Munsell colour scale. Unfortunately, standards for comparison are neither convenient nor inexpensive, and no method of colour description has come into general use. The need for a routine method is very urgent, and it may be hoped that it will be met in the near future. (See p. 261.) In the meantime, the writer has found the Ridgway colour atlas very convenient for laboratory determinations of colour.

SOIL ANALYSIS FOR ADVISORY PURPOSES

If our knowledge of the constitution of the soil were more complete, there would be no need to draw a distinction between soil analysis for scientific purposes and soil analysis for advisory purposes, because a complete specification of the soil would not only describe the soil but also supply all the information necessary for giving advice to farmers on the manurial treatment of their land and for diagnosing causes of poor performance. In the absence of any complete under-

standing of the constitution of the soil and of the chemical and microbiological changes taking place in it, there has grown up in each country a body of analytical methods, mainly empirical, designed to answer specific questions. For example, there is a wide choice of methods that purport to answer the question: Is this soil in need of a dressing of lime or chalk and, if so, at what rate should it be applied? To answer this question it is necessary (1) to make certain analytical determinations and (2) to interpret the results of these determinations. The very wide choice of methods reflects the great divergence of opinion about the relevant determinations, whilst the interpretation of the analytical data requires that they shall be related to a wide range of circumstances such as crop, season, and possibly economic conditions, in the light of available experience. It is therefore incorrect to speak of determining the "lime requirement" of a soil. The actual requirement is largely a matter of opinion in the light of certain analytical data.

Soil analysis for advisory purposes as carried out is largely empirical, yet, as practised by experienced advisers, can give valuable aid to the practical man. The underlying principle of much of this work is the determination of so-called "available" plant nutrients. It was realized at an early stage that total analyses of the soil can give little useful information, and many methods of extraction have been proposed whereby the available may be distinguished from the unavailable plant nutrients. Thus, B. Dyer⁷ originated the widely used method of extraction with 1% citric acid. Other methods involve the use of such extractants as N/5 nitric acid, N/200 sulphuric acid, and N/2 acetic acid.

It is not our intention to discuss these methods in detail but it may be helpful to examine some of their underlying principles.

In the first place it should be realized that there is no clear distinction between "available" and "unavailable." For example, there are many categories of soil phosphorus, both inorganic and organic. Some are more and some are

less available; yet even the most insoluble may contribute to some extent to the phosphate nutrition of plants.

Secondly, whatever extractant is used, each category of a given plant nutrient will have a certain solubility in it, although some will be more and some less soluble.

Thirdly, in most methods of extraction the amount of a particular ingredient extracted will be affected by such factors as ratio of soil to solvent, time and method of shaking, and temperature. With few exceptions, the methods are conventional.

Fourthly, whatever method is used it is necessary to interpret the results. To answer the simple question as to what constitutes deficiency, laboratory results must be related to field behaviour, and this implies the setting up of carefully designed field experiments with different crops over a number of seasons.

The choice of suitable analytical methods and their correct interpretation are the foundations on which soil analysis for advisory purposes rests. There are great difficulties at each stage. An analytical method must not only give significant results; it must also be adaptable for use with large numbers of samples. Here spectrographic and photo-electric methods have proved of great value. The interpretation of analytical data presents its own special difficulties and is often highly subjective.

Given the difficulties of using soil analysis as a basis for advisory work, it is not surprising that other methods have been sought for diagnosing the plant nutrient status of soils. Of these alternative methods, the pot technique of E. A. Mitscherlich⁸, in which the response of crops grown in a given soil to increasing doses of fertilizer is studied, has attained a wide use in Germany. Another approach is that by H. Neubauer and W. Schneider, in which seedlings grown on the soil are analysed for manurial ingredients. There is also the *Aspergillus* method of H. Niklas, G. Wilsmeier, and F. Kohl¹⁰, in which fertilizer requirements are deduced from the growth of the mould *Aspergillus niger*

on preparations of the soil with varying additions of nutrient elements. The concordance of the results of these methods with soil analytical methods has been discussed by E. A. Mitscherlich¹¹. It seems clear that no single method will give trustworthy information in all cases, but that there are a number of methods that can prove satisfactory in a majority of cases.

An entirely different attack on the problem is by using the growing plant for diagnostic purposes. Pioneer work in this field was done by H. Lagatu¹², and the technique has been considerably developed during recent years by T. Wallace¹³ and his collaborators. Considerable use may be made of the diagnosis of nutrient deficiencies from discolorations and other appearances on leaves. Atlases have been prepared showing the symptoms of manganese, potassium, boron, iron, and other deficiencies on the leaves of different crop plants. This method has been reinforced by the development of sensitive colour reactions for assessing the status of leaf tissues in respect of some important plant nutrients. The method is probably capable of development and extension, but even when perfected must suffer from the disadvantage that the deficiency is discovered only after the plant has started into growth. For this reason, plant nutrient diagnosis, however satisfactory it may be in revealing a nutritional deficiency or imbalance, can never be so helpful to the practical man as methods that will enable him to take the necessary measures before crop growth begins. Diagnoses from foliar examination is probably more helpful in the case of tree and bush growth than in the case of annual field crops, where the deficiency may be discerned too late for remedial measures to be taken. Yet even here, early diagnosis may often permit action to be taken in time to save a crop. For example, manganese deficiency in oats can be diagnosed in the early stages and the immediate application of manganese sulphate in spray form can save the crop.

From what has been said it is clear that there is no generally accepted system of soil analysis in examination for

advisory purposes. Nor is such a system in sight, because given the importance of interpretation the widely differing conditions in different countries and regions must lead to a variety in advisory methods.

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CHAPTER XX

SOILS, PLANT GROWTH, AND AGRICULTURE

THE purpose of this work is mainly to present an account of the soil as a natural object of study. We have purposely refrained from presenting the problems of the soil from the standpoint of crop production, partly on account of the complexity of the considerations involved and partly because a satisfactory understanding of the nature of the contract between the soil and the living plant must be preceded by a thorough understanding of the constitution of the soil. Yet an account of the soil as a natural object would be incomplete without some reference to its relationship to the higher plants which inhabit its surface. For this relationship not only constitutes the chief human interest in the soil, but is also of direct importance in the study of the development of the soil itself.

NUTRITION OF PLANTS

The dry matter of plants consists of organic matter, and mineral or ash constituents. The principal constituents of organic matter are :—

Carbohydrates, including sugars, pectins, and starches.

Fibres.

Oils, fats, and waxes.

Proteins.

The carbon, which forms about 55-60% of the dry organic matter, is obtained by the process of carbon assimilation or photosynthesis from the carbon dioxide which forms about 0.03% of the atmosphere. This change consists

essentially in the formation of starch from carbon dioxide and water, probably through formaldehyde and dextrose as intermediate stages, with concomitant liberation of oxygen. The reaction, or chain of reactions, is endothermic and the source of energy is the sunlight. A further condition for the process is the presence of chlorophyll, the green colouring matter of plants. Except in so far as carbon dioxide is produced in the soil by the oxidation of organic matter, the soil cannot be considered as of direct importance in carbon assimilation. The hydrogen and oxygen of organic matter are obtained ultimately from the soil moisture.

The remaining elements of the dry matter of plants, namely, nitrogen, and the elements present in the ash, namely, sulphur, phosphorus, calcium, magnesium, potassium, iron, silicon, and all the other elements which, though not in all cases essential to growth and reproduction, normally occur in plants, are obtained from the soil.

Additions are constantly being made to the list of elements considered necessary for plant growth. Thus, during recent years, manganese, boron, copper, zinc, and iodine have been shown to be essential. They were overlooked by earlier workers on account of the minute quantities required relative to the other nutrient elements. The traces of impurities present in the materials used for culture solutions were often actually sufficient to supply these elements. It is likely that the list of nutrient elements will be further enlarged. Progress is limited by the inadequacy of ordinary analytical methods. The adoption of spectrographic methods has enabled considerable advances to be made in the survey of the essential elements for plant growth and their occurrence in soils. In the meantime, it is possible that some of the obscurer cases of infertility in soils may be due to unascertained deficiencies in trace elements.

It is generally supposed that the elements thus obtained, often termed plant nutrients, enter the plant root by absorption from the soil solution; and much of the theory of plant nutrition has been built up on the basis of experiments in

which plants are grown in so-called culture solutions. It is possible, however, that the mode of absorption by the plant may not be so simple as this theory implies. N. M. Comber¹ has put forward the suggestion that the colloidal material of the soil and the colloidal material of the plant roots may form a single system within which translocation of material may take place. Whatever be the nature of the contract between soil and plant, it is evident that a principal duty of the soil is to furnish the growing plant with an adequate and balanced supply of the nutrient elements. In many soils, mycorrhizal associations may be of great importance for plant nutrition.

There are, however, other factors involved in plant growth. Apart from the water required for the actual material of plants, water is required by the roots of plants to make good the constant losses by transpiration from the leaves. It has been found that, for every part by weight of dry matter formed, from 200 to 1,000 parts by weight of water are required. The supply of water to plants is intimately bound up with the supply of oxygen needed for the respiration of the root system of plants. An excess of water, whilst not necessarily disadvantageous in itself, restricts the air supply to roots. On the other hand, an excess of air, not in itself harmful, implies a deficiency of moisture. Between the two extremes lies the optimum, which is often considered to be fulfilled by a 50% saturation of the pore-space of the soil with water.

The ease with which the soil yields up water to plants diminishes as the moisture content decreases below the optimum. Finally, a point is reached at which the water is so firmly held by the soil colloids that the losses by transpiration can no longer be met, and wilting, i.e., loss of turgidity, occurs. The moisture content at the *wilting point* is roughly represented by 4.2 on the pF scale (p. 283). It is thus evident that the moisture present in a soil is not entirely available to plants, but is subject to a deduction that is dependent on the colloidality of the soil.

Each plant has its own minimum, optimum, and maximum temperature for germination and also for adult growth. The value of any particular situation or soil for plant growth is therefore relative to the plants which can grow there. Plant growth cannot take place below 0°C , but certain arctic and alpine species can grow at temperatures immediately above freezing point. At the other extreme are plants which can tolerate temperatures up to $45\text{--}50^{\circ}\text{C}$. The optimum temperature for growth varies considerably among different plants.

Generally speaking, the temperature of the soil is closely related to that of the air; but, as we have seen in Chapter IV, minor differences may occur among soils even under the same climate. In regions where the growing season is limited by winter, such minor differences may be of considerable importance in their effect on the beginning and duration of the year's growth.

The next factor to be considered is negative, namely, the absence of injurious or toxic substances. The most obvious cases of inhibition of plant growth due to this group of factors are seen in soils in the vicinity of lead, copper, tin, or zinc mines, where the presence of compounds of these metals partially or entirely excludes vegetation. The considerations advanced in discussing "trace" elements in nutrition are applicable to injurious elements. Cases of infertility may occur where the injury is due to small traces of elements whose presence in the soil has hitherto been unsuspected.

Another type of injury due to harmful constituents is that caused by the presence of excess of soluble salts, most commonly sodium chloride, sulphate, or carbonate. There is a considerable variation in the tolerance of different plants to soluble sodium salts. Indeed, some plants, natives of the sea shore and of saline soils, may be described as halophytic. Most economic plants, however, can tolerate only small concentrations of salts in the soil moisture, and the presence of such salts is a serious drawback to the agricultural use of soils in which they occur.

Finally, there is the possibility of injury or limitation of plant growth through the presence of acids, or, defining the case more strictly, the prevalence of an excessive concentration of hydrogen-ions in the soil moisture.

The problem of soil acidity in its relationship to plant growth has been for many years the subject of laborious investigation and active debate. That certain soils fall below satisfactory productiveness by reason of the prevalence of conditions that can be remedied by the application of dressings of lime or calcium carbonate cannot be doubted. That acidity in itself is the injurious factor cannot be so generally maintained. It is certainly true that an extreme degree of acidity, such as is rarely found in ordinary soils, is injurious to plant growth. It is also true that a reaction slightly on the acid side of neutrality may inhibit the activity of the nitrogen-fixing bacterium *Azotobacter*, and in so far as this activity is a necessary part of the nitrogen economy of the soil, acidity is harmful. Otherwise, most plants can tolerate a fairly wide range of reaction, although the optimum reaction for individual species varies somewhat.

The problem is complicated by the fact that soil acidity cannot enter into the problem of soil fertility as an independent factor, for it is correlated with a deficiency of available calcium and also, in some cases, with the presence of actively toxic aluminium compounds. Indeed, M. Trénel and F. Alten² have demonstrated in culture solutions that aluminium, active below pH 5.0, acts as a specific root poison. Further, in some cases, soil acidity may be correlated with undesirable physical conditions. It is thus not easy to assert generally that soil acidity, *per se*, is a limiting factor. The limitation may actually be due to lack of available calcium, the presence of active aluminium, or the prevalence of an undesirable physical condition.

SOIL FERTILITY

We have enumerated the principal groups of factors affecting the growth of plants: the list may not be exhaus-

tive, for other factors may be involved. For optimum growth all factors must operate satisfactorily. The unsatisfactory operation of a single factor, such as the supply of moisture or available nitrogen, may offset the satisfactory operation of all other factors. Where it is possible to use a quantitative expression, e.g., nitrogen supply, a relationship can be

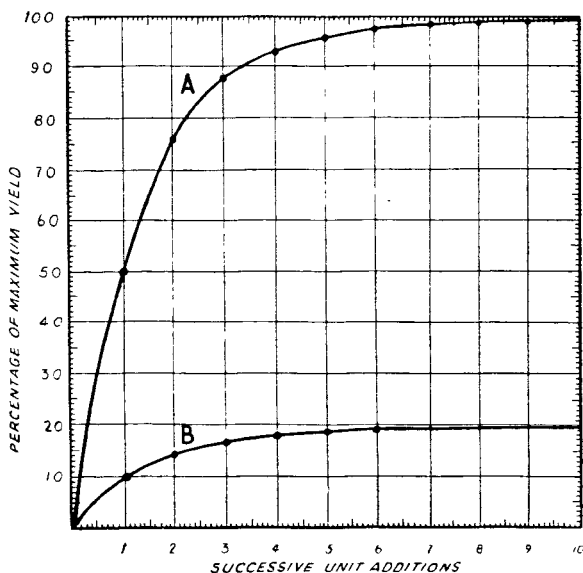


FIG. 22.—Response Curves.

traced between the magnitude of the factor and the yield obtained. Many equations have been devised to exhibit this relationship. The simplest is that which assumes that the increment in yield for each successive unit increment in the factor is proportional to the deficit from the maximum yield obtainable. In the form of an equation this may be stated as—

$$dy/dk = k(A - y).$$

Where y is the yield, x is the growth factor, e.g., nitrogen

supply, A is the maximum yield and k is a constant. If we term one unit the amount of the growth factor necessary for 50% of maximum yield, the relationship between the magnitude of the growth factor and yield would be as follows :—

Units	Yield as % of maximum
1	50
2	75
3	87.5
4	93.7
5	96.7 and so on.

These relationships are illustrated by the curves in *Fig. 22*. In curve *A* is shown the theoretical response to successive unit additions of a plant nutrient, for example, nitrogen, assuming that all other factors are operating satisfactorily. Curve *B* shows the way in which the yield may be modified when one or more of these other factors operate unfavourably. Here the maximum yield obtainable by increasing the supply of the nutrient in question is much smaller, but the form of the response curve is similar.

Curves showing the relationship between yield and the magnitude of any growth factor such as nitrogen or phosphorus supply are known as *response curves*. The response of a crop to a given addition of any plant nutrient will depend on two circumstances, namely, (1) the amount of the nutrient already present and (2) the maximum yield possible as determined by the operation of the remaining factors. Thus a low response to a dressing of fertilizers may be obtained either because the nutrient is already present in abundant supply or because some other factor or factors, e.g., water supply or lime supply, are so deficient that only a small yield is possible whilst these deficiencies are unremedied.

The actual yield of a particular crop will depend on a great variety of factors, including seasonal variations and even casual factors such as the incidence of diseases and pests, so that it is somewhat difficult to assign to any soil a

numerical assessment of productivity. If such an assessment were possible it would be necessary to take into account (1) the soil factors, (2) the site factors, including climate, and (3) type of management and crops or stock raised.

The concept of soil fertility is, as we have seen, very complex. Apart from this, it is necessary to note the different sense in which the term is actually used. In different contexts the term fertility may bear any of the following senses :—

(1) Soil fertility may be taken to mean the productivity of the soil, as measured by the yield per acre. This is sometimes termed “productivity rating” and is arrived at by calculating a weighted average of the principal crops grown each yield being expressed as a percentage of a supposed maximum. This estimate may be further elaborated by giving the rating for ordinary management and for the best type of management.

(2) Soil fertility may be regarded as a measure of the response given by the soil to expenditure in labour and materials. It is this that principally determines the agricultural value of a soil and the rent that the farmer is prepared to pay for it, although other factors such as accessibility to markets and other economic factors may also play a part in determining this value.

There is no absolute scale of fertility, because the use to which the land is put must be taken into consideration. Some soils are chiefly valuable as pasture, and the most famous fattening pastures retain their reputation and value only when used as pasture. Other soils may be valued highly for arable farming, others for market gardening or fruit culture. In the case of irrigated lands the natural productivity may be almost negligible, but the return for cultivation when irrigation works are installed may be very great indeed.

(3) A third sense in which the term fertility is used is that of plant nutrient status. This rather restricted use of the term is more common in the United States than in this

country. Yet many writers may inadvertently use the term in this sense, without explanation.

It would help considerably towards an adequate treatment of the problems of crop growth if terms such as soil fertility and soil productivity were used in a more precise sense.

PROBLEMS OF CROP GROWTH

We may review briefly the problems which the pedologist is called upon to solve when he assumes the rôle of agricultural chemist and attempts to give assistance to practical agriculture.

Firstly, he is called upon to show how soil productivity measured in yield per acre or hectare can be most economically increased. To answer these questions he must know the effect of cultivation and management, crop rotation, and manurial practice on plant growth under the particular conditions of climate and soil encountered in his district or country.

Secondly, given the particular type of land utilization, he should be able to lay down the conditions under which yields may be maintained at an economic level and the soil guarded against deterioration and loss.

Thirdly, he must be able to prescribe the measures to be taken, if economic conditions should demand a change in the system of land utilization.

It must be admitted that the present state of our knowledge falls far short of that necessary for the adequate solution of these problems—in so far as they apply to the actual growth of crops. Yet their solution is urgent at the present day, when there is such a serious world shortage of food. Plan and order are necessary alike for expansion and restriction.

There appear to be two approaches to the solution of the problems of soil fertility and soil management. In one, knowledge is acquired by observing the effect on crop production of various methods of cultivation, management,

cropping, and manuring. By isolating the variables and applying the latest statistical methods the results thus obtained can be given the highest significance. The results of such experiments contribute little to increasing our knowledge of the master-problem of the contract between soil and plant, yet they are necessary in order to solve immediate problems.

There is also another approach, namely, the study of the master-problem of plant nutrition and growth. The pursuit of fundamental knowledge needs no justification, for this is the classical road by which science has passed on its gifts to practical life.

Field experiments must always be carried out, particularly in undeveloped countries face to face with new problems, but the writer would deplore any avoidable diversion of material resources and creative thought into this pedestrian type of investigation, which opens out no new horizons, but merely answers the commonplace questions it is required to solve.

If it is conceded that the surest approach to the practical problems of crop production is through fundamental research on plant physiology, the task of the pedologist is to elucidate the constitution and properties of the soil in order that the plant physiologist, when he carries his investigations from the artificial culture solution to the soil itself, may find a medium whose reactions are accurately known and whose significant properties can be specified in precise quantitative terms. The progress which has been made in the study of the soil itself during recent years encourages the belief that the time is ripe for an attack on the problems of plant nutrition along the lines indicated in the above discussion.

SOILS AND AGRICULTURE.

The earliest cultivations of soil were in arid and semi-arid regions, and it has been shown that in the westward migrations into Europe the first settlements were in forest-free regions, the loess areas, which in their general character

resemble steppe. For primitive agriculture, the steppe or prairie offers a much better prospect for successful crop production than the forest soils of humid regions. Under steppe, the climatic conditions, though drier than in humid regions, are more dependable. There is generally sufficient moisture after the winter for the establishment of crops, whilst the hot dry summer is favourable to ripening and harvest. Further, the moderate leaching tends to the conservation of plant nutrients and the inhibition of the deteriorative processes which operate in humid soils. The chief problem is water supply and yields are determined mainly by this factor. It is significant that the principal wheat areas are on the black earths and the chestnut earths.

All agricultural soils were formerly virgin soils. In long-settled countries most of the soil has been in agricultural use for centuries, and the profile characters of the primitive soils have been profoundly altered during the centuries. In newer countries, such as the United States and the Argentine, many soils still retain some of the characteristics of the virgin soils from which they have been reclaimed.

A comparison of virgin with cultivated soils is instructive. Under virgin conditions, soils and vegetation form a system that is in a state of dynamic equilibrium. The mineral plant nutrients abstracted from the soil in each season's growth are returned in leaf fall or by the decay of herbaceous and annual plants. It is true that in forests there is an annual storage of plant food due to tree growth, but in the absence of human interference this material is ultimately returned to the soil as trees die and decay. The only losses are in the form of drainage. Against this may be offset the gains from the weathering of minerals in the soil. Under such conditions it is not surprising that luxuriant vegetative growth is possible with a comparatively small supply of available plant food, of which a considerable proportion is in circulation between vegetation and soil.

This equilibrium is completely destroyed when the virgin soil is brought into cultivation. The available plant

food in circulation suffices to give a satisfactory or even a heavy crop at first, but as each crop is removed from the soil the supply shrinks and yields fall off. If cropping is continued, yields are stabilized at a low level determined by the balance between losses by drainage and crop removal on the one hand, and the gains due to weathering of minerals and nitrogen fixation on the other. If production is to be at a higher level the inevitable losses by drainage and crop removal must be made good by addition of manures and fertilizers. In the case of nitrogen, fixation by bacteria can balance to some extent, in some cases completely, the losses by drainage and removal of crops.

We may now proceed to consider the probable consequences of bringing into cultivation different kinds of virgin soil. For this purpose we shall consider four typical cases, namely :—

- (1) Podsollic soil, associated with coniferous forest or heath.
- (2) Brown earth or grey-brown podsollic soil, associated with deciduous forest.
- (3) Prairie soil, associated with tall-grass vegetation.
- (4) Chernozem, associated with short-grass steppe.

(1) Considering first the podsollic soil. In its natural state it is characterized by very low base-status, an organic layer of raw humus, and a loose structure in the mineral A-horizon. This soil, even if used under an “acid” type of agriculture for such crops as oats, potatoes, and hay, requires immediate dressings of lime or chalk to correct the lime deficiency, to decompose raw-humus, and to promote the development of crumb-structure. It would certainly need phosphatic and potash fertilization, and would probably need nitrogen also to induce biological activity. In permanent cultivation podsollic soils would need regular calcareous dressings in order to make good the inevitable losses by leaching.

The humid climate would favour utilization as grass-land, but grass on such soils is liable to degeneration unless carefully managed. It is therefore advisable, after a number of years in grass, to introduce an arable break and to seed down afresh. This is the type of agriculture practised in Wales. With attention to calcareous and phosphatic dressings a fairly high level of productivity is possible; otherwise degeneration is rapid.

(2) Brown earths have an advantage over podsoils in their better base-status, owing either to the character of the parent material or to the drier soil climate. Raw humus is absent and the soil structure is better than in the first case. The drier climate is more favourable to arable husbandry and grain crops would offer fewer anxieties than under the wetter climate of the podsoils. Although good crops would be obtainable at first, the need for calcareous, phosphatic, and potash dressings would soon be felt. Under continuous arable cultivation there would be the danger of organic matter being lost by biological oxidation. This would be accompanied by loss of structure and the danger of erosion in climates where periods of intense rainfall occur. Although the climate may not be humid enough for exclusively grass husbandry, temporary leys are desirable to maintain the organic matter status. For the same purpose, animal husbandry, with its production of farmyard manure, is of great importance.

(3) Prairie soils developed under tall-grass vegetation are characterized by higher base-status than the brown earths. They are also richer in organic matter and possess well-developed crumb structure. When first brought into cultivation they yield heavy crops, which are fairly well maintained for some years, even under continuous cultivation, particularly if rotations are suitable and if live-stock husbandry is practised. The initial base-status is higher than that of the brown earths and podsoils but applications of lime may eventually become necessary. With the drier climate, the chief peril is depletion of organic matter. The

climate is favourable for cereals, whilst the maintainance of artificial grassland is rendered difficult by periodic droughts. Soils of this type occur in the most productive agricultural regions of the United States, as in Iowa, Illinois, and Missouri.

(4) Chernozem soils developed under short-grass vegetation have still higher base-status and better developed crumb structure. Good crops are obtained at once and are well maintained without the need for dressings of lime. The dry climate favours cereal production, but there is also the risk of occasional crop failure through drought. Under continuous and exhaustive exploitation, they lose organic matter with consequent deterioration in structure. They then become subject to wind erosion. Most of the serious wind erosion in the United States and Canada during recent years has occurred on these soils.

Each soil has its own inherent tendencies to deterioration; on the soils of humid climate, owing to lowering of the base-status, and in arid climates owing to loss of organic matter. The maintenance of permanent agriculture depends on the understanding of these tendencies, and the practice of types of agriculture that will counteract their operation. The serious consequences of neglecting to establish permanent systems of agriculture, and of robbing the accumulated fertility of virgin soils may be seen in the vast areas of ruined soils in the United States and in many parts of the tropics.

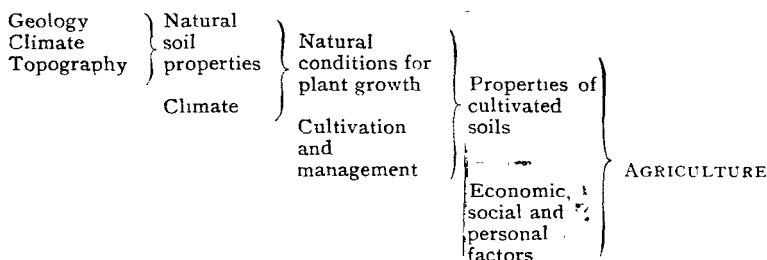
So far as Europe is concerned, with the exception of Spain and parts of Southern Europe, the utilization of the soil has proceeded along rational lines. In the opinion of the author, however, it is a mistake to rely too much on arable culture with the maintenance of fertility by the use of artificial fertilizers. A type of husbandry, such as that practised in Wales, in which the soil is periodically laid down in grass, may offer possibilities of economically increasing production. Land in grass accumulates fertility whilst providing food for grazing animals. When ploughed

up it has many of the characters of a prairie soil. It is, of course, difficult to establish temporary grassland in regions with hot dry summers, but considerable progress has been made in the technique of sowing down to grass. The introduction into the rotation of a period under grass might be of considerable value in the systems of agriculture practised in central and eastern Europe.

In spite of the more intensive agriculture of north-western Europe, the cultivator must constantly struggle against conditions that militate against arable culture. One of the principal differences between soils of the chernozem group and soils of the podsollic group is in their structure. Whilst the calcium-saturated soils of the former class naturally tend towards the desirable crumb structure and demand a minimum of cultivation, the podsollic soils tend to assume the single-grain structure. The cultivator is therefore always attempting to establish a structure which is purely artificial. The leaching consequent on the high rainfall results in an impoverishment in mineral constituents, principally lime, which, if unchecked by applications of calcareous dressings, eventually results in deterioration, accompanied by loss of the desirable crumb structure. The actual labour of husbandry is increased by the fight against weeds and the anxieties of harvest operations. High yields can be obtained in arable farming in the humid districts of western Britain; but it should be realized that, since the natural vegetation is forest or heath, constant effort is necessary to prevent deterioration. It is perhaps no exaggeration to say that the efforts of the farmer in the humid regions are directed towards the production and maintenance of artificial chernozems. Having said this, it must also be said that some of the most successful agriculture and the most productive land occurs on these soils where the skill of the farmer is pitted against the tendencies of the soil to become impoverished.

The agriculture of a particular locality is the reflection of a complex of factors, of which climate, soil, and situation are the most important, since they impose certain limits on

the choice of crops for cultivation. But economic, social, and even personal factors also intervene, with the result that the agriculture of a country only partially reflects the variations in soil and climate within its borders, and may undergo changes from generation to generation in response to causes other than those arising from fundamental natural factors. The inter-relationships of these factors may be thus represented schematically :—



SOIL CONSERVATION AND PERMANENT AGRICULTURE

In a period of agricultural depression, when the tendency is towards restriction of effort, deterioration is likely to ensue, and to be most pronounced in those regions where conditions are most artificial. The consequences of "low farming" are likely to be less serious where conditions approach more closely to those of the steppe and the prairie.

The tendency to degeneration of soils in humid temperate regions is always present, but the highly developed agriculture of countries such as England, Holland, and Belgium, is sufficient proof that the struggle against it is no impossible task and that, with cheap fertilizers and skilful husbandry, crop yields can be obtained that would not be possible in drier regions.

Under the conditions of the humid tropics, the maintenance of an artificial system of land utilization is beset with even greater difficulties. The tendency to deterioration of virgin land brought into cultivation is far more rapid than in temperate climates. The high temperatures lead to a very rapid destruction of reserves of organic matter with conse-

quent deterioration in physical condition, whilst the torrential tropical rains, acting on such soils, produce vigorous erosion. It is not surprising, therefore, that there are many instances of newly broken soils becoming completely derelict within a few years through injudicious management.

Cultivated soils are, to a large extent, artificial and show profiles that may differ markedly from the corresponding virgin profile. From the moment that the original cover of natural vegetation is destroyed, the processes that have produced the original succession of horizons are modified, and new factors, leading to a new profile succession, are introduced. Loss of organic matter is the commonest consequence of cultivation and may be demonstrated under practically all climates when pioneer cultivation is instituted. F. T. Shutt³ gives an instance of a Manitoba prairie soil which showed a decrease of nitrogen content from 0.651% to 0.506%, and of ignition loss from 19.43% to 14.79%, as the result of 25 years of cultivation. The writer found a cultivated soil in Caernarvonshire to contain 0.490% nitrogen, and to have an ignition loss of 16.6%, whilst the adjoining waste, from which it had been reclaimed, contained 1.106% nitrogen and gave 43.1% ignition loss.

Loss of organic matter is not the invariable consequence of bringing land into cultivation. Where grass husbandry is practised, or where heavy dressings of organic manures are given, as in market gardens, the organic matter content of the soil may be maintained or even increased. In general, the loss of organic matter is least where livestock farming is practised, for it is then possible to return to the soil a considerable proportion of the crops raised and fed to stock, in the form of manure.

In many parts of the world, the most serious consequence of cultivation is erosion. We have already referred to the widespread erosion in the Eastern United States, which has taken place within comparatively recent times. Through uninstructed utilization of land in past generations, much irreparable damage has been done over large areas of

the tropics and sub-tropics. It is important, therefore, that future agricultural operations should be conducted with the fullest possible precautions against further losses.

The crops obtained immediately after bringing virgin land under cultivation are always bigger than succeeding crops. It is the common experience that yields fall off as the land is longer under cultivation. Under virgin conditions, the demands on plant nutrients are comparatively slight, for a large proportion of the nutrients extracted from the soil by plant roots is returned to the soil again in the form of plant residues. Under pioneer cultivation, the soil is cropped continuously and deterioration is inevitable. Firstly, there is a rapid exhaustion of plant nutrients as crop after crop is removed, and secondly, there is, in many cases, a physical deterioration in the soil consequent on loss of organic matter. This is manifested by a decreased water-holding capacity and an increased liability to erosion.

Even where the land is not brought under actual cultivation, uncontrolled grazing may lead to deterioration of the soil. Examples of this may be cited from South Africa, where injudicious grazing and close folding (*kraaling*) has led to a destruction of the natural cover. The consequence of this has been erosion by gullying, resulting in lowering of the water-table, and accentuation of the effects of drought.

The deterioration consequent on pioneer cultivation of virgin land may be checked where live stock husbandry is practised, for it is then possible to return to the soil a considerable proportion of the nutrients extracted from it by crops. Organic matter may also be maintained by green manuring. The introduction of artificial fertilizers, whereby the plant nutrient status of the soil can be controlled, marks a further stage in land utilization. With the present abundance and cheapness of fertilizers, the serious problems of continuous agriculture are mainly physical in character. Indeed, in some systems of agriculture, crops are grown almost entirely on added fertilizers, and the rôle of the soil is mainly physical. This is the case over a large part of the cotton lands of the United States.

The utilization of land for irrigation brings its own set of problems. In many instances, the continued addition of irrigation water has led to a rise in the water-table, whereby injurious salts have been brought to the surface. In other cases the irrigation waters used contain excess of sodium over calcium salts, with the result that the irrigated soil is gradually changed from a calcium to a sodium soil with consequent deterioration and ultimate disaster to crops. Fortunately, the behaviour of saline and alkaline soils has been so thoroughly studied that the pedologist can afford immediate help in proposing remedial measures for soils threatened by deterioration through alkalinization.

During the past 150 years the tendency has been towards an increase in the agricultural production of the world as a whole. This has been fostered by the settlement of virgin lands, by industrial development, which has rendered possible the application of machinery to agriculture, and by the astonishing progress of agricultural science, which has shown how greater yields may be extracted from the soil by the use of artificial fertilizers. Progress in the practice and science of agriculture goes on at an ever-increasing rate. It might appear, therefore, that the future food supply of the world is in no danger of proving inadequate to the needs of world population.

A more careful consideration of the position, however, may lead to a less optimistic view of the future position. In every continent there are vast areas that were once productive but are now represented by ruined soils of negligible agricultural value. This deterioration may be due to desertization, as in central Asia and North Africa, to wind erosion, as in the western states of the U.S.A., to water erosion, as in parts of Southern Europe, in the eastern states of the U.S.A., and in the humid tropics, or to the salinization and alkalinization of irrigated soils, as in Mesopotamia, South Africa, and California. In every case, reckless exploitation of the soil has led to deterioration and ruin. In past centuries this has been less culpable because of the

limitation of man's knowledge of the soil and his ignorance of the probable consequences of the use that he was making of it.

When to these limitations are added the disorganization due to wars and their aftermath, the prospect of abundant and cheap food throughout the world appears very remote, even although some countries may experience temporary abundance. With vast areas of soil irreparably or almost irreparably ruined through unwise exploitation, and with fuller knowledge of the causes of this destruction, soil conservation becomes as important an aim as the expansion of agricultural production. Soil deterioration may be rapid or gradual, but immediate gains in food supply are dearly bought if they lead to the ultimate impoverishment or ruin of the medium from which they are obtained. The first question to be asked by those responsible for the agricultural policy of any country is, therefore, whether the use made of the soil is such as to ensure that this soil shall continue to be capable of yielding reasonable returns for the labour of the cultivator. The existence of the Soil Conservation Service in the United States is evidence that the maintenance of the soil is a major objective in the nation's future agriculture. Other countries also have become unceasingly aware of the importance of conserving their soil.

In western Europe and particularly in Britain, the equable character of the climate and the prevalence of rational and conservative systems of land utilization render the fear of soil destruction fairly remote. Here the danger is rather that the potentialities of soil and climate are not realized to the full. Anyone familiar with practical farming knows that the difference in output between land poorly farmed and the same land well farmed is very great indeed. In the experience of the writer the adoption of "good husbandry" on Welsh farms in place of "hand to mouth" farming has resulted in an approximate doubling of production as measured by stock-carrying capacity. Without any revolutionary changes in farming practice, a general grad-

ing up of the standard of husbandry, including the improvement of the vast areas of marginal grazing, might produce a striking increase in food production from British farm lands.

The destruction of soils under cultivation, though operative only in certain regions, is, for the future, a menace to the world supply of food and other commodities obtained from the soil. Much of the damage done in past generations is well-nigh irreparable, and the prevention of further losses is one of the main tasks confronting the pedologist. Hitherto, the practical aims of soil investigation have been chiefly concerned with the increase of crop growth. In future, the problems of soil conservation must claim more attention, particularly in view of the potential developments of tropical agriculture. These problems demand the most ample elucidation of the constitution and properties of the soil. The successes that have been obtained encourage the hope that the fullest utilization of the world's soil resources may not be incompatible with the conservation of those resources by systems of permanent agriculture. *There shall be an handful of corn in the earth upon the tops of the mountains* (Ps. lxxii, 16).

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